A PLM IMPLEMENTATION

FOR

AEROSPACE SYSTEMS ENGINEERING-

CONCEPTUAL ROTORCRAFT DESIGN

A Thesis
Presented to
The Academic Faculty

by

Peter Bartholomew. Hart

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Aerospace Engineering

Georgia Institute of Technology
May, 2009

A PLM Implementation for Aerospace Systems Engineering- Conceptual Rotorcraft Design

Approved by:

Dr. Daniel Schrage, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Mark Costello
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Alan Whilhite
School of Aerospace Engineering
Georgia Institute of Technology

Date Approved: April 3, 2009

ACKNOWLEDGEMENTS

Thank you to Dr. Daniel P. Schrage for his guidance over the years as an advisor, employer, father figure, and friend.

Thank you to the committee members Dr. Alan W. Wilhite, National Institute of Aerospace-Langley Distinguished Professor, and Dr. Mark Costello, Sikorsky Associate Professor in Rotorcraft Technology, and all of the professors I have studied under. Their expertise and recommendations proved invaluable in the completion of the course work and thesis.

I would like to thank all of the Administration and Staff of Georgia Tech with whom I have dealt over the past few years. I sincerely appreciate your patience and understanding in helping me to achieve my goals.

I am grateful to Mr. Tord Dennis of Siemens PLM Software, and Vincent Fox of University of California-Davis for their technical support.

I am also grateful to Dr. Peter Rohl, Dr. Sayeed Paydarfar, Dr. Joe Holland, and Mr. Steve Wegner for encouraging me in my professional growth as a PLM enabled Aerospace Vehicle Systems Design Engineer.

Lastly, I would like to sincerely thank my fellow Aerospace Engineering graduate students, past and present, as well as my former students in the College of Engineering at Georgia Tech. Your fellowship has been the guiding light to my discovery, enlightenment, and accomplishment.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
LIST OF TABLES	v
LIST OF FIGURES	vi
LIST OF SYMBOLS AND ABBREVIATIONS	ix
SUMMARY	xii
SCOPE	xv
MOTIVATION	xvii
METHODOLOGY	xxiv
CHAPTER	
1 BACKGROUND	1
2 KINGFISHER VEHICLE CONCEPT	7
3 REQUIREMENTS DATA MANAGEMENT	17
4 CUSTOMER REQUIREMENTS	45
5 ENGINEERING REQUIREMENTS	56
6 QUALITATIVE ANALYSIS	73
7 QUANTITATIVE ANALYSIS	92
8 PRODUCT STRUCTURE ARCHITECTURE	109
9 TOOLSET INTEGRATION	120
10 CONCLUSIONS	133
11 FUTURE WORK	139
APPENDIX A: ORIGINAL TEXT OF THE 2001 AHS RFP	148
APPENDIX B: 2001 KINGFISHER PROPOSAL	149
APPENDIX C: TCSE INSTALL NOTES	150
REFERENCES	151
VITA	155

LIST OF TABLES

	Page
Table MO.1 - DoD 5015.02-Standard Subpart Contents	xviii
Table 3.1 - DoDAF requirements to use an Enterprise Architecture	33
Table 4.1- Import Keywords for Customer Requirements Extraction from RFP	51
Table 5.1 - List of Core Engineering Requirements for Rotorcraft	57
Table 6.1 - Several of the 7 MaP Tools used in IPPD	74
Table 8.1 - Work Breakdown Structure Definition	112
Table 8.2 - Common Work Breakdown Structure Elements for Aircraft Systems	113
Table 11.1 - Frequency of Major Activities in a Vehicle Lifecycle	144

LIST OF FIGURES

	Page
Figure M.1-A PLM enabled Design Engineering Methodology	xxiv
Figure M.2-The GT Generic IPPD methodology	xxvi
Figure M.3-A PLM-Enabled Digital System Engineering Environment	xxvii
Figure 2.1-The UH-60 and the "Perfect Storm"	8
Figure 2.2-AHS RFP Mission Profiles Requirements	10
Figure 2.3-Kingfisher Advanced Technology SAR Rotorcraft System	11
Figure 2.4-Kingfisher Technology Candidates for Advanced Flight Controls	14
Figure 3.1-Discrete Steps in Engineering Design Process	18
Figure 3.2-Broad Area Maritime Surveillance (BAMS) Area Announcement	19
Figure 3.3-Design Changes vs. Time Source: "The House of Quality"	20
Figure 3.4-A Generic Product Life Cycle	22
Figure 3.5 -Egg Chart for Requirements Engineering Consumption	24
Figure 3.6-Teamcenter Systems Engineering Software Architecture	27
Figure 3.7-Teamcenter Systems Engineering Component Installation	28
Figure 3.8-TCSE GUI: Administration Area	29
Figure 3.9-TCSE GUI: TCSE User Area	30
Figure 3.10-A Digital Enterprise Configuration	38
Figure 4.1-Example Complex System Customer Requirements: BAMS	47
Figure 4.2-Example Complex System Customer Requirements: BAMS	48
Figure 4.3-Import Methodology of AHS RFP using automated keyword extraction	50
Figure 4.4-Imported Kingfisher Customer Requirements in TCSE	52
Figure 4.5-Advanced Search Function in TCSE	53

Figure 4.6-Requirements Parsing using Advanced Search Function Results in TCSE 53
Figure 4.7-Derived Customer Requirements with Group Assignment in TCSE 54
Figure 5.1-Kingfisher Engineering Requirements in TCSE 58
Figure 5.2- Teamcenter Community/TCSE Integration 61
Figure 5.3- Teamcenter Community Main Project Site 62
Figure 5.4- Teamcenter Community Document Library 64
Figure 5.5-Common Digital Content Formats 65
Figure 5.6-Teamcenter Workflow Manager 67
Figure 5.7-Teamcenter Automatic Notifications 68
Figure 5.8-Teamcenter Community Survey Creation 69
Figure 5.9-Teamcenter Community Survey Conduction 70
Figure 5.10-Teamcenter Community Survey Conduction 71
Figure 6.1-Kingfisher Customer Requirements in Affinity Diagram 76
Figure 6.2-Kingfisher Engineering Requirements in Affinity Diagram 77
Figure 6.3-Group Item Type Requirement Assignment in TCSE 78
Figure 6.4-Kingfisher Engineering Requirements in Tree Diagram 81
Figure 6.5-Kingfisher Inter Relationship Diagram 84
Figure 6.6-Kingfisher Inter Relationship Diagram Visio/TCSE 85
Figure 6.7-Kingfisher Morphological Diagram for the SAR.IPPD 88
Figure 6.8-Example Image of Trace Link Function 91
Figure 7.1-Flowchart of Qualitative Requirements Analysis 93
Figure 7.2-Generic Quality Function Deployment (QFD) Method 95
Figure 7.3-Original 2001 Kingfisher QFD Matrix 96

Figure 7.4-QFD Methodology Baseline tool in Triptych 99

Figure 7.5-Kingfisher QFD Method in Triptych/TCSE Tool 99

Figure 7.6-QFD Correlation Matrix of Engineering Characteristics 101

Figure 7.7-Cascading QFD Matrices 102

Figure 7.8-Distributed QFD Matrices 103

Figure 7.9-Vehicle Characteristics created as Building Block Item Types in TCSE 105

Figure 7.10-Pugh matrix for the Kingfisher Vehicle Configuration 107

Figure 7.11-Pugh matrix for the Advanced Flight Control System 107

Figure 8.1-Functional Building Blocks 110

Figure 8.2- Work Breakdown Structure for 2001 Kingfisher, Level 2 114

Figure 8.3-Work Breakdown Structure in TCSE 4 Level 115

Figure 8.4-Work Breakdown Structure for 2001 Kingfisher, Level 4 115

Figure 8.5-Work Breakdown Structure in TCSE 4 Level 116

Figure 8.6-Work Breakdown Structure as Visio/TCSE Integration 117

Figure 8.7-Work Breakdown Structure as Building Block Item Types 118

Figure 9.1-Siemens PLM Software Suite of Teamcenter Integrated Products 121

Figure 9.2-Teamcenter Community/TCSE Integration 123

Figure 9.3-Teamcenter Community Main Kingfisher Collaboration Site 124

Figure 9.4- Teamcenter Community Collaborative Conferencing Application 125

Figure 11.1-Original PLM Enabled Design Engineering Method w/ Optimization 140

Figure 11.2-To-Be Lifecycle of Integrated Data Managers with Feedback Loops 142

LIST OF SYMBOLS

7 MaP	7 Management and Planning Tools
ACSYNT	AirCraft SYNThesis Tool
AE	Aerospace Engineering
AEE	Advanced Engineering Environments
AHS	American Helicopter Society
BAA	Broad Area Announcement
BAMS	Broad Area Maritime Surveillance
CAA	Computer Aided Analysis
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CATIA	Computer Aided Three Dimensional Interactive Application
CE	Concurrent Engineering
CERT	Center of Excellence for Rotorcraft Technology
CFD	Computational Fluid Dynamics
CG	Center of Gravity
COTS	Commercial Off the Shelf
CIE	Computer Integrated Environment
CQI	Continuous Quality Improvement
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DFSS	Design for Six Sigma
EA	Enterprise Architecture
EBOM	Engineering Bill of Materials
EOL	End of Life
EPA	Environmental Protection Agency
FCS	Flight Control System
FEA	Finite Element Method Analysis
GT	Georgia Tech
GTAE	Georgia Tech Aerospace Engineering Department
GUI	Graphical User Interface

IDE	Integrated Digital Environment
IPPD	Integrated Product and Process Design
IPR	Intermediate Project Review
IPT	Integrated Product Team
JRE	Java Runtime Environment
MADM	Multiple Attribute Decision Making
MBOM	Manufacturing Bill of Material
MDO	Multiple Disciplinary Design Optimization
MRO	Maintenance and Repair Overhaul
NARA	National Archives and Records Administration
OEC	Overall Evaluation Criteria
OCR	Optical Character Recognition
PCC	Product Change Control
PCCM	Product Configuration Change Management
PDM	Product Data Management
PDR	Preliminary Design Review
PLM	Product Lifecycle Management
PSA	Product Structure Architectures
QFD	Quality Function Deployment
RFP	Request for Proposal
RMA	Records Management Application
RDM	Requirements Data Manager
RSM	Response Surface Methodology
SAR	Search and Rescue
SDD	System Design and Development Phase
SDI	Statistical Design Institute
SE	Systems Engineering
SDK	Software Development Toolkit (JAVA)
SME	Subject Matter Expert
STS	Space Transportation System

TCC	Teamcenter Community
TCENG	Teamcenter Engineering
TCMFG	Teamcenter Manufacturing
TCSE	Teamcenter Systems Engineering
TRL	Technology Readiness Level
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VTOL	Vertical Takeoff and Landing
WBS	Work Breakdown Structure

SUMMARY

The modern aerospace vehicle manufacturing business enterprise is under extreme pressure to create high technology products more rapidly and with reduced cost. Business managers are increasingly reliant on decision support infrastructures to make the right decisions at the right times to insure affordable product development. This is especially true for complex products such as aerospace vehicle systems, which have long lead times and high costs for product development. One method of reducing the time and costs of development is through the re-use of strategic design knowledge created during previously successful product developments. The extent that an enterprise can rely on this capability has been recently eroded due to the reality of an aging workforce and talent migration in a downturn economy. One solution then is to develop a modern framework for knowledge capture and re-use to ensure enterprise viability throughout the full spectrum of economic contexts. The presented research will detail the methodology and provide an example demonstration of accomplishing this solution.

The System Engineering implementations of Concurrent Engineering and Integrated Product and Process Design (IPPD) best practices have recently been successful in streamlining product development. It is suggested by the current research that these methodologies be improved in the System Engineering phase of conceptual product development. Addressing these issues in the front stages of vehicle development can provide significant time and cost reductions across all of the downstream product lifecycle phases. This could be accomplished through the digitization of an IPPD methodology using newly available Product Lifecycle Management (PLM) component

technology. In PLM, a dedicated Requirements Data Manager (database) is created for digital requirements engineering. A Commercial-Off-the-Shelf (COTS) database tool called Teamcenter Systems Engineering (TCSE), by Siemens PLM Software, is deployed. TCSE will be investigated in terms of its ability to provide for knowledge capture and re-use of both legacy and innovation data sets. In addition, the Requirements Data Manager could provide a central repository to coordinate the participation of geographically distributed subject matter experts in the integrated product teams (IPTs). This thesis will attempt to show how the coupled use of PLM and a digitized systems engineering process can significantly reduce the time and cost of conceptual design.

The thesis details the benefits of deploying an Integrated Computer Environment, TCSE, that could provide significant reductions in the effort associated with product configuration and change management (PCCM). Reductions in these areas provide Continuous Quality Improvement (CQI) benefits throughout all of the product lifecycle phases. This is accomplished in the research through digital linking of requirements to their compliant entities within the multiple System Engineering tools and Product Architectures. Linking provides precise traceability of product development logic within the requirements data sets, in a readily usable format. This in turn enables surgical modification of the configuration data, given proper authority through a change management process. An additional benefit of this methodology is to examine whether program transparency may be achieved through the continuous visibility of requirement engineering data subsets to a third party regulatory or contracting agency. Establishment and demonstration of this modern design environment characteristic is important due to the fact that it is consistent with current standard Department of Defense (DoD)

contracting terms. It also anticipates near term Environmental Protection Agency (EPA) regulation compliance activities for banned materials and processes.

In order to illustrate the methodology, viable aerospace vehicle conceptual design data is used to populate the proposed PLM environment. The example vehicle is an original design for an advanced search and rescue helicopter concept, capable of performing "The Perfect Storm" mission, as depicted in the film of the same name. An innovative technology aspect is incorporated into the vehicle design through a requirement for an "advanced flight control system." This vehicle example uniquely illustrates the capabilities and utility of a digital IPPD methodology coupled with a dedicated Requirements Engineering Database. Estimated time and cost reductions are calculated based on the deployment of the proposed environment. The thesis concludes by suggesting the creation of a requirements engineering template that could conceivably be used to support future rapid (rotorcraft) vehicle design developments.

SCOPE

The scope of this thesis is the conceptual design of an original rotorcraft vehicle. The vehicle configuration type is a tiltrotor to meet the stated need for an advanced search and rescue VTOL aircraft for heavy weather endurance. The Requirements Engineering phase of an original Conceptual Design Engineering Methodology for Aerospace Vehicle Synthesis is researched to provide tools for the consideration of all aspects of the design, including:

1. Propulsion
2. Vehicle Configuration
3. Speed/Range
4. Flight Controls
5. Crew and Passengers
6. Mission Capability
7. Performance

with special emphasis placed on the advanced flight control system.

The thesis prescribes a modern Computer Integrated Environment composed of digitized System Engineering tools used in conjunction with a Requirements Data Manager. An entire suite of system engineering tools, including the 7 Management and Planning (7 MaP) tools and QFD, are reviewed on a tool by tool basis.

Teamcenter Systems Engineering, a Siemens PLM Software database tool is installed, configured to integrate Microsoft Office productivity tools, and used to accommodate and manage the example flight vehicle system engineering data sets.

The topics of requirements authoring, multi-disciplinary design optimization (MDO), and the linking of datasets within the Requirements Data Manager (RDM) to

those residing in a Product Data Manager (PDM), are beyond the scope of this thesis. It is for this reason that these topics will be mentioned in context, but not discussed in absolute detail.

MOTIVATION

The main motivation to streamline the systems engineering phase of conceptual design is compliance with governmental regulatory mandates. These legal mandates are generally echoed by the Private Sector in their corporate processes and recommended best practices. The deployment of Systems Engineering methodologies in defense systems acquisition is required by law. Specifically mandatory procedures have been enacted for programs subject to DoD Directive 5000.1 [2], and DoD Regulation 5000.2-R [3]. These regulations identify the responsibilities in the acquisition process from the Secretary of Defense to the Department of Defense component field offices. They deal with the processes and procedures necessary to create the Work Breakdown Structure (WBS) as the primary activity towards initiating the System Design and Development (SDD) phase of Defense System Acquisition.

The DoD 5000 series Directive and Regulations are specific in the mandate of processes to be conducted and consistent in their statement that component Systems Engineering best practices must be employed. In addition, the DoD 5015.02-Standard "mandates the functional requirements for Records Management Application (RMA) software, defines required system interfaces and search criteria that RMAs shall support ; and describes the minimum records management requirements that must be met based on current National Archives and Records Administration (NARA) regulations." [4] A synopsis of the DoD 5015.02 Standard is given in Table MO.1.

DoD 5015.02 Standard-Detailed Requirements:

2.1.1 Implementing File Plans

2.2.2 Scheduling Records

2.2.3 Declaring and Filing Records

2.2.4 Filing Electronic Mail Messages

2.2.5 Storing Records

2.2.6 Retention and Vital Records Management

2.2.7 Access Controls

2.2.8 System Audits

2.2.9 System Management Requirements

2.2.10 Additional Baseline Requirements

Table MO.1: DoD 5015.02 Standard Subpart Contents detailing Electronic Records Management (RMA) requirements for all organizational entities with the Department of Defense. [4]

It is to the benefit of all parties involved to accomplish the mandated compliance with the multiple DoD directives in an efficient and cost effective manner. The Return on Investment that may be realized is alluded to in the commentary of the Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics) below. It can be seen that this statement could just as easily apply to private industry, as well as academia.

"DoD's new acquisition vision provides a process that promotes the kind of acquisition, technology, and logistics excellence that enables us to maintain our technological superiority by fielding (to our users) the best systems with available technologies that are supportable, interoperable, and affordable in less time and at less cost. In changing our strategy for systems development and acquisition, as outlined in our new DoD 5000 policy documents, my objective is to reduce cycle time and achieve an average of five to seven years from program launch to production." [5]

Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics).

Based on the large amount of regulatory information being developed and integrated into DoD Systems Acquisition Processes, this thesis seeks to address many of the challenges proposed. It would be most beneficial to conduct an investigation into the state of the art for Advanced Engineering Environments (AEE) to discover a pathway towards compliance with the newly released mandates. This is an ambitious endeavor. However, it can be made more achievable by the focus on a single phase of an example product lifecycle that is representative of the challenges encountered in the DoD world.

In 2001, graduate students at Georgia Tech Aerospace Engineering (GTAE) responded to the 18th annual Design Competition RFP issued by the American Helicopter Society International (AHS). The Request for Proposal was specifically targeted towards the development of "Advanced Rotor Control Concepts." This dictated that the design team conduct a normal design investigation of a mission-based rotorcraft vehicle concept, with the additional task of synthesis and analysis of "Advanced Flight

Control Concepts." The team quickly discovered that additional preliminary work needed to be done in order to arrive at a vehicle configuration (conventional, tandem, tiltrotor…) decision prior to the work on the advanced flight controls.

The team was concerned with the large amount of time dedicated to the relatively routine tasks of a vehicle configuration down-select study and interpreting the provided customer requirements. The time spent on these two tasks was disconcerting; in light of the fact that they had been accomplished by the team only one semester previously for an unrelated rotorcraft design project. (Joint Heavy Lift) Due to the lack of digital data organization and an automated requirements engineering methodology, the team found itself repeating the tasks, manually, as was common practice at the time. This included a completely new IPPD team activity, using the 7 MaP and QFD tools in an environment consisting of yellow Post-It Notes, and colored markers. The team down-selected the Tilt Rotor configuration as the baseline for their 2001 AHS design.

Following the configuration downselect, the team was unable to rapidly define a set of engineering requirements which would support a vehicle architecture, due to the non-existence of useable legacy data on Tilt Rotor Designs. This was in spite of the fact that two complete Tilt Rotor vehicle designs had been recently realized by GTAE in 1997 and 1999. The 2001 team was forced to rely on sparse industry docs, questionable commercial Tilt Rotor marketing media and the two end result design reports from 1997 and 1999.

As a direct result of these events, the 2001 team was faced with the near certainty of proposing an inappropriate blade control technology, due to the lack of time available for synthesis and comparison among flight control system candidate technologies. Worse

yet, the proposal submission deadline could be missed altogether, based on these delays. Sadly, the 2001 team was beaten by a superior design for active blade control. In retrospect, one could easily attribute the loss to a large amount of time spent performing what could have been routine engineering tasks, leveraging legacy datasets. The situation suggested a major change in design methodology was necessary to reduce the time to develop the vehicle concept at the systems engineering phase.

Through the implementation of PLM technology at the Systems Engineering phase, an Integrated Digital Environment (IDE) could be created to support rapid concept iterations and subsequent investigations in step with Design Maturity. The PLM environment could provide for a total rotorcraft vehicle system engineering data set to be versioned and archived. This would make it available to future engineers, in a familiar format, who may desire to re-visit the design as-is, or to leverage detailed aspects towards innovative new designs. The time saved could be significant (on the order of weeks, out of a 20 week total effort), and result in an enhanced capacity to explore a design space in greater detail, which is often necessary with designs that feature challenging new and emerging technologies.

In the past, there have been two minds of thought in the pursuit of this type of digital environment. The first advocated a custom designed software environment that called up custom designed sub-routines as necessary to arrive at a relatively narrow spectrum of solutions. This would be similar to the AirCraft SYNThesis (ACSYNT) and FIPER environments. The second, and more recent approach, has advocated the use of web-based resources and JAVA to accomplish a similar task of calling various analysis

routines for disciplinary studies and creating output media in the form of a dashboard view of the design.

The drawbacks to both of these approaches is that neither advocates the use of a dedicated database environment for residence of both requirements (inputs and output files) and analysis tools, with versioning and role-based access control. Both legacy approaches require advanced level knowledge and dedicated expertise in the Computer Science disciplines, as a distraction from Aerospace Engineering. These competencies are not commonly available to the graduate level teams at GTAE who are the primary users of such systems. In addition, the two approaches are relatively static solutions tied directly to the single vehicle design space at hand. Substantial code reworking is required for each minor change in the design space (for example, high altitude or heavy weather endurance; tilt rotor or unmanned).

The thesis proposed system engineering phase of a PLM-enabled Conceptual Design methodology offers a clear alternative to the two emergent methods. It provides an intuitive graphical user interface and user customizable environment options to suit application to the broad spectrum of complex disciplinary products. As a true database, with roles defined privileges, workflow assignments can flow directly from physical product architectures; automatically distributed to knowledge workers, with an associated digital "paper trail." This provides a streamlined change management and scheduling management capability not found in the legacy approach systems. Commonly used, COTS analysis routines are promoted, rather than custom designed software being incorporated into a spaghetti of compiled code that is extremely difficult to troubleshoot by an engineer when runtime errors occur. The strength of the PLM-enabled design

environment is an ability to provide traceability of design decisions/assumptions directly to the supporting data. This allows for the subsequent surgical change of data to be investigated in context, without the need for complex optimization routines.

The true measure of the value of an IDE for Systems Engineering is not in the ability to create customized software for data representation, but in the ability to rapidly provide clear, concise decision making support to the IPT and engineering management. This capability remains as an industry challenge to this day. The utility of the proposed environment in meeting this challenge is expressed in the following quote:

> "The Right Data should be made available to the Right People, at any time/place that they need it, to provide the Ultimate Customer Experience. Do this in as simple and affordable manner as possible. Also do this in a manner so that this process (asset) may be re-used for ANY product, around the world."
>
> Pete Hart, 2008 [6]

METHODOLOGY

This thesis will discuss the Requirements Engineering phase of an original Conceptual Design Engineering Methodology for Aerospace Vehicle Synthesis which is depicted in Figure M.1. The thesis will demonstrate the ability to significantly reduce design time by automating Requirements Engineering for Conceptual Design through the application of COTS PLM technology. An integrated software framework is defined and used in the demonstration of the methodology.

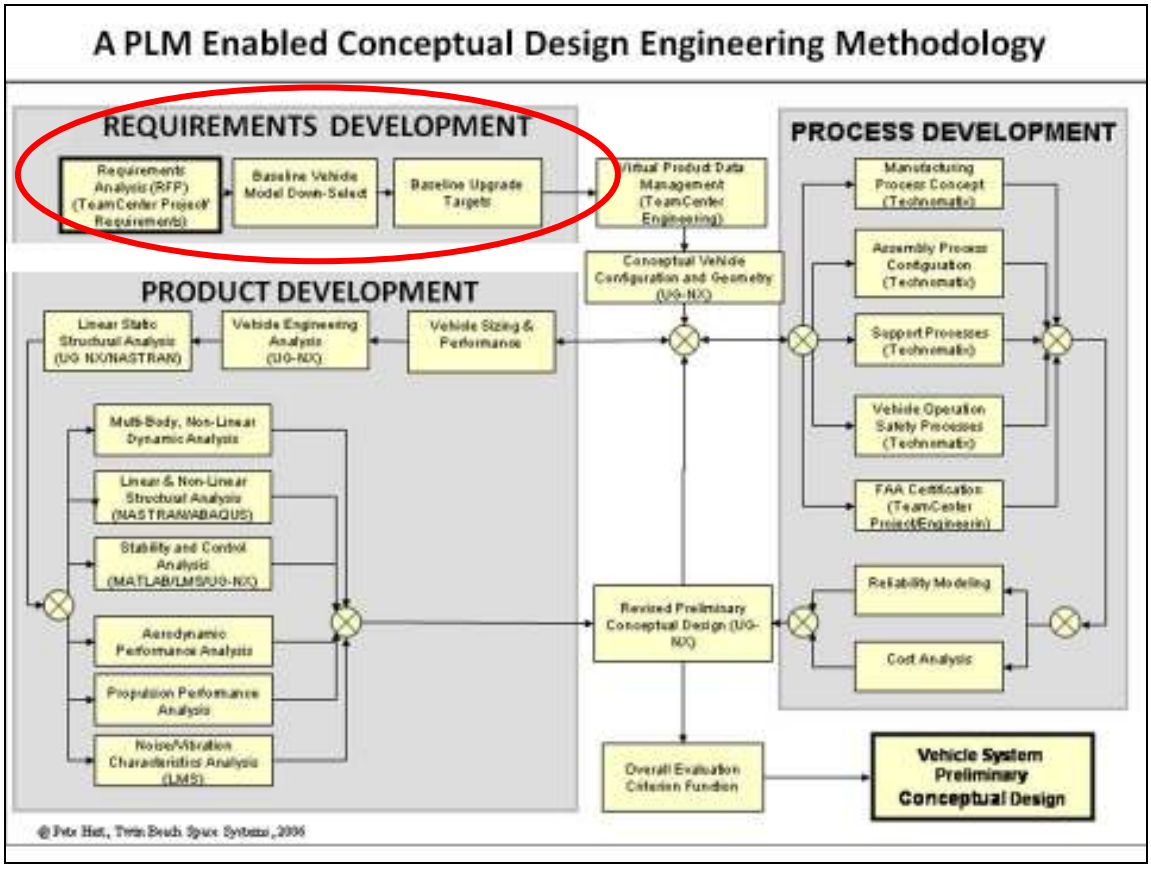


Figure M.1: An original PLM enabled Conceptual design methodology, showing the concurrent consideration of both the Product and the Manufacturing Processes associated with the Product. The thesis focus area is highlighted with a red oval. Hart, 2009 [7]

An example application of the method will consider a representative set of Rotorcraft Vehicle customer requirements. In order to insure example relevance, the 2001 Request for Proposal (RFP) for the 18th Annual AHS International Student Design Competition is used. A set of functional engineering characteristics is synthesized through the newly digitized use of the 7 MaP and QFD System Engineering tools, and the GT-IPPD Methodology, shown in Figure M.2. The requirements dataset will be analyzed both qualitatively and quantitatively to achieve multiple candidate functional architectures. Resulting functional and physical architectures are used to create a Work Breakdown Structure in preparation for downstream design engineering. All of the associated datasets for requirements and tools are shown reside within a deployed Teamcenter Systems Engineering database tool. This will complete the demonstration of the digital systems engineering environment for conceptual design.

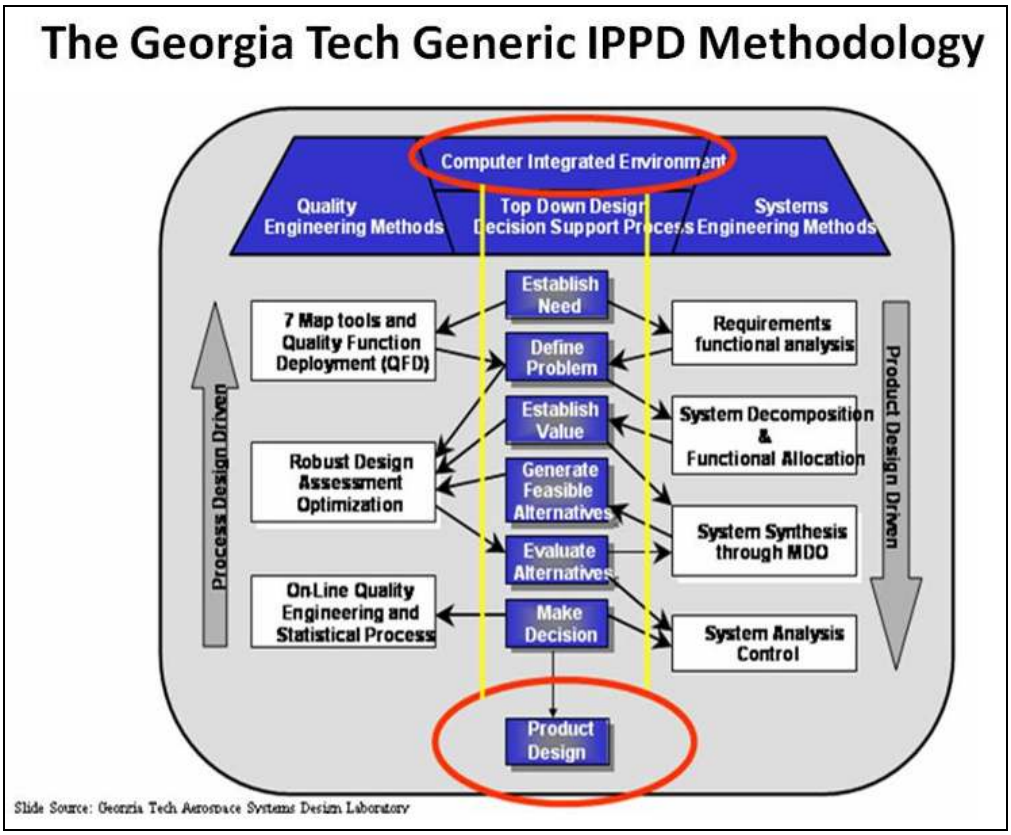


Figure M.2: The Georgia Tech Generic Integrated Product and Process (IPPD) Methodology. Kirby, 2001 [8]

The following list outlines the major methodologies used to accomplish this research:

1. Automated Import of User Requirements
2. Automated Parsing of User Requirements per engineering disciplines (Propulsion, Structures, Controls, Layout, Safety, Advanced Technology…)
3. Qualitative Synthesis of Engineering Requirements Version using the 7MaP tools
4. Logical “trace linking” of Customer and Engineering Requirements
5. Quantitative Analysis of Requirements using QFD

6. Automated Digital Synthesis of Functional and Physical Product Structure Architectures (PSA) Version
7. Automated creation of WBS Version
8. Consideration of MDO, Response Surface Methodology (RSM)
9. Consideration of Linking to Teamcenter Engineering
10. Template creation through Versioning of the Project Data set in TCSE

Figure M.3 depicts an overall block diagram for gross software tool relationships and basic design data flow.

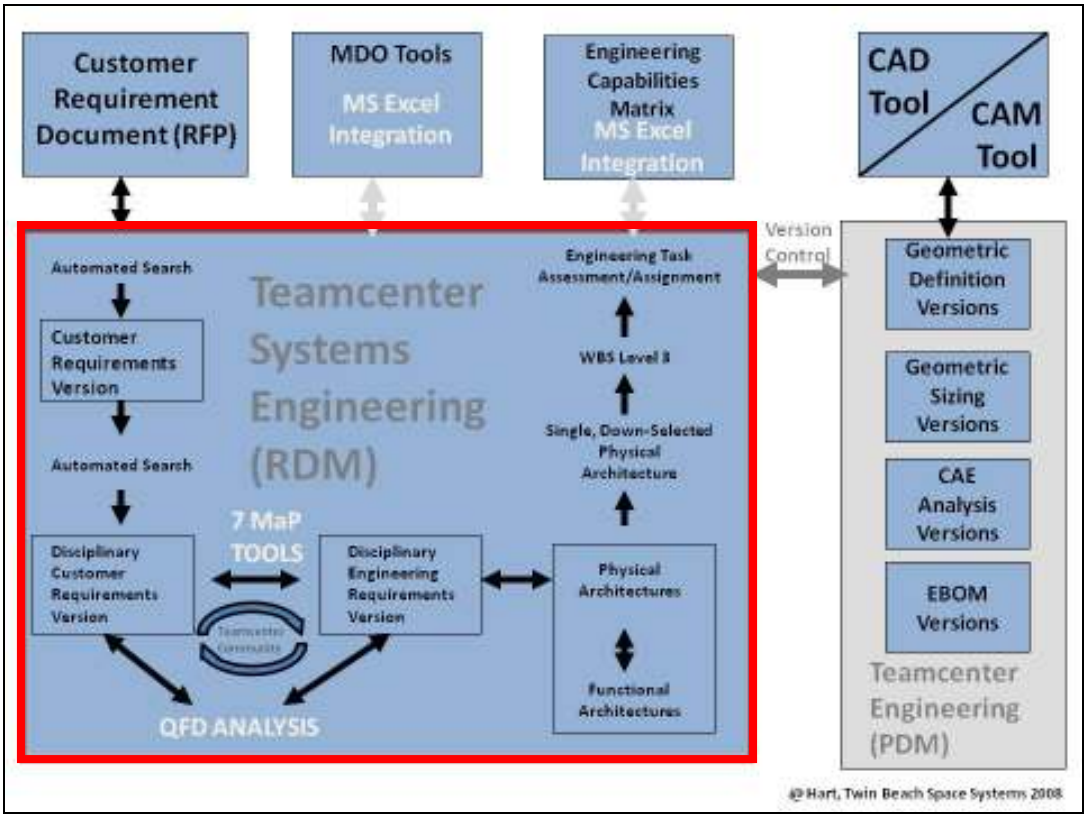


Figure M.3: "A PLM Enabled Digital System Engineering Environment". Data flow through the environment is depicted in the black arrows. The current thesis focus area is defined with a red border. Hart, 2009 [9]

The above described Computer Integrated Environment will be accomplished through the coordinated installation and employment of the following COTS software tools:

-Word, Excel, Visio-Microsoft Office

-Teamcenter Systems Engineering (TCSE)-Siemens

Installation of the Server, Database and Web Components

System Administration and Configuration of the TCSE tool

Project administration and Configuration of the Kingfisher project

Project Execution at the User Level

-Teamcenter Community

-Design for Six Sigma Tools (DFSS), QFD-Triptych, Statistical Design Institute

-JAVA Software Development Toolkit (SDK)–Sun Microsystems

-Java Runtime Environment (JRE)

-.NET Framework-Microsoft

-Tomcat Web Application Server- Apache

-Versant Database

-Virtual PC Environment-Microsoft

-Sharepoint Services-Microsoft

-Windows Server 2003-Microsoft

-Windows XP, SP3-Microsoft

CHAPTER 1

BACKGROUND

The current research is the latest endeavor to define a new Design Engineering methodology for the 21st century. The goals of this ongoing effort are to leverage newly mature computer hardware and software technologies to streamline the effort necessary to produce cutting edge design innovations. These innovations are necessary to compete and win in the production of (student team) Design Proposals in response to industry based RFP's. The expected cumulative effect of the new methodology is reduced time to design through automation and integration of existing diverse toolsets to accomplish traditional engineering tasks. The ability to provide visualization and management of engineering data provides enhanced decision making support to rapidly increase design value, at an affordable price.

The current research is built upon previous work in Concurrent Engineering, which dictates that both the Product and the Manufacturing Process be realized simultaneously during the Conceptual Design phase of development. This mandate is clearly depicted in flowchart form in Figure M.1 shown previously.

The methodology was intended to act as a roadmap for IPT to accomplish designs in an efficient procedural manner. In order to adopt the methodology, teams found themselves confronted by the unavoidable need to use the computer to digitally accomplish traditional engineering calculations. Conveniently, a first generation of digital tools existed, based on the maturity of FORTRAN programming, and post-mainframe era computer technology. These were mainly stand alone analysis routines, proposed for

narrow disciplinary applications. The tools used the command line interface, and were often used only for the most intense compute tasks that were difficult if not impossible to perform by manual calculation. The results were either numeric or code-text based which were difficult to relate to team members without substantial review. There was a need to identify a tool that would incorporate the full spectrum of design data into a more meaningful decision support format. Computer Aided Design (CAD) provided just such a tool.

CAD Modeling

Early CAD modeling had limited functionality as a quicker way to produce blueprints. However, once high performance graphics cards became available in desktop computers (2002), interactive 3D CAD was possible, and affordable. CAD provided the design teams with a fully parametric model of the vehicle design, which was available in a dynamically shaded 3D visualization. Engineers were empowered to relate the latest results of their various sizing and analysis tools to a single CAD model of the vehicle. Unknowingly, this formed the first crude "database" repository for the disciplinary spectrum of design data. The CAD geometric definition formed a versioned dataset that could be queried for additional data, such as weight, center of gravity (CG), and Principle Moments, etc.

Extensive use of the CAD tool by team members culminated in the synthesis of a standardized methodology for aerospace vehicle geometric definition based in a modern CAD authoring tool: CATIA v5. Several aspects of the variational parametric geometry definition were refined to form standardized best modeling practices. This provided a coherent organization of data, resulting in improved readability, and time savings.

-Nesting of parts, sub-assemblies, and assemblies to provide standard 3D geometric layouts that can be analyzed efficiently.

-Use of part model linking to provide dynamic associativity between the hull surface definition and dependent structural member definitions.

-Rapid development of virtual reality visualization of 3D styling.

- Development of a station based fuselage definition strategy to automate refinement and re-generation of lofted hull surfaces based in parametric curves driven by vehicle configuration.

Design/Analysis

In 2004, the challenge of an integrated design/disciplinary analysis methodology was addressed. At this point, the CAD model morphed from acting as an OUTPUT repository to added use as the INPUT to disciplinary Computer Aided Engineering (CAE) tools. Finite Element Analysis Methods (FEA) used a subset of the vehicle CAD model defined by the structural components arranged in a logical load path layout. Meanwhile, Computation Fluid Dynamics (CFD) utilized the subset of the Outer Mold Line Surfaces to perform drag studies, supporting associated propulsion estimations. Controls Simulations relied heavily upon the Principle Moments, Weights, and CG calculated within the CAD model. The CAD best practices were further refined to provide an easy extraction of each of these data sets, without undo effort, or compromising the overall integrity of the CAD model. This resulted in:

-Effective configuration management of both design and analysis datasets, by single source of geometric data version to all CAE toolsets.

- A greatly reduced time to analysis, through integrated CAD/CAE.

-Accurate CAD definitions eliminated the need to produce low fidelity abstractions as CAE input.

-Rapid iteration of the CAE input files through adjustment of the CAD model.

Process Definition

The use of the design methodology depicted in the left side of Figure M.1 greatly improved the reliability of the engineering design data associated with Vehicle Concepts. However, it did little to address the "Second P" in the IPPD method- Manufacturing Processes. Process modules are contained on the right side of the flowchart in Figure M.1. In 2005, design teams spent considerable time deploying a capability similar to CAD, for Computer Aided Manufacturing (CAM) by using a tool called DELMIA. DELMIA is a "sister tool" to CATIA, in that they share a common Graphical User Interface (GUI), and common data programming. Similar to the use of CAD model inputs by CAE tools, DELMIA was able to directly use CAD model inputs to define 3D manufacturing and assembly simulations. Investigations were accomplished into the assembly and operative processes associated with a design, as a further means of establishing design validation, specifically in the areas of time to fabricate, human factors, design usability, supportability, and cost.

Computer Integrated Environment

A substantial level of integration had now been accomplished between the sizing tools, CAD, CAE and CAM tools, reducing the time to engineer. But, the engineering data existed on individual desktop computers in digital form, detached from a "Common Design Intent" dictated by the original Customer Requirements. The engineering was

accelerated. But it could be going in the wrong direction, losing the time that had been saved! This often became evident during IPR presentations, much to the disappointment of all involved… The only solution in this situation is to re-consider the engineering requirements synthesized from the RFP, and perform a second iteration on the Product (and associated Process) Loops in Figure M.1. In the best situation, a coherent data organization would be reviewed to identify the data sub-sets affected by the re-direction, and a quick iteration made on the design. The reality is that this does not often occur. It is often very difficult to determine with accuracy which engineering data is supportive of individual engineering requirements.

A need was identified to provide an environment to act as a dynamic repository for digital Requirements Engineering data which could be digitally related to the engineering data described previously. The proposed environment has been historically illustrated as the "Computer Integrated Environment" (CIE) in the GT Generic IPPD Methodology Flowchart, depicted in Figure M.2. However, to date, the CIE has not been effectively realized.

The proposed creation of a Computer Integrated Environment creates issues for Requirements Engineering during the traditional use of the 7 MaP tools, and QFD (Figure M.2). These are often accomplished by hand on yellow Post-It Notes with multi-colored markers. Following the manual use of the 7MP tools, a static JPEG image is composed and displayed in reports and IPR presentations. However, a JPEG image cannot be digitally deconstructed to provide data supporting downstream engineering activities. The problem is how to digitally conduct and capture the 7 MaP and QFD tool content in a manner that provides bi-directional dynamic relation to a versioned set of Requirements.

Data Residence and Management

There was a realization that the familiar desktop operating system file structure was insufficient to provide adequate support for new design data organization and access by the team. The same was true for legacy design data organization and access. A short term solution was devised of creating a central server based “Team Design Account”, where all relevant data sets would reside. However, it was discovered that this was not a foolproof solution, as each team member had the ability to create, re-organize, change or delete data sets. In addition, the team was forced to assume that all uploaded data sets had been peer reviewed for content and accuracy, and were approved for use. This was not always the case, and led to the use of inappropriate data, based solely on the fact that it had been uploaded to the team account. The system failed in the areas of:

-Data Organization, with auto versioning, and archive of vehicle evolutionary design

-Design Configuration Management and Release Control

-File content search (as opposed to Filename Search)

-Individual Parameter Value Location, and versioning

-Remote Access, Collaboration, and Distribution of Data

-Lack of a Decision Making "Trail of Breadcrumbs", with roles based accountability.

The current research attempts to demonstrate a dedicated database tool to function as the digital Computer Integrated Environment for Systems Engineering.

CHAPTER 2

KINGFISHER VEHICLE CONCEPT

In order to illustrate the capabilities of the proposed Computer Integrated Environment and methodology, a representative rotorcraft vehicle concept was chosen. The vehicle design concept was developed by an IPT composed of graduate students (including the author), in the rotorcraft engineering program at Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. The design was created in response to the 2001 Graduate Rotorcraft Design Competition RFP issued by AHS [9]. This is a challenging annual competition, with a new RFP issued each year for a unique, advanced technology rotorcraft vehicle system. A text of the original 2001 AHS RFP is contained in Appendix A.

The RFP challenged the graduate student team to propose a conceptual rotorcraft design for a heavy weather Search and Rescue mission profile. An additional feature of the RFP was the stipulation that an innovative approach to advanced Flight Controls must be incorporated into submitted proposals. The challenge was further defined as a vehicle capable of performing the SAR mission in extremely bad weather-similar to that endured by the UH-60 Blackhawk Helicopter as depicted in the year 2000 movie "The Perfect Storm," shown in Figure 2.1.

Figure 2.1: Image of the UH-60 Jayhawk, similar to the vehicle that ran out of fuel and crashed in heavy weather, far offshore of New England, as depicted in the movie "The Perfect Storm" [11] The Kingfisher vehicle was designed to create a capability for search and rescue in heavy weather, avoiding such tragedies.

To propose on the RFP, an integrated product team was formed consisting of graduate students from the Georgia Tech Aerospace Engineering Center of Excellence for Rotorcraft Technology (CERT). The team followed a traditional, manual, IPPD methodology to create a vehicle concept and baseline physical architecture that could be refined by subsequent CAE, CAD, CAM, investigations. At the conclusion of the necessary investigations, a single Design Proposal was submitted for consideration to the AHS Graduate Competition Committee.

The design and the proposal report were accomplished as a homework assignment for academic courses in rotorcraft design. The courses feature a wealth of legacy information on aeronautical engineering and rotorcraft theory in specific. However, the AHS work was done with very little benefit from previously published GT designs on

similar (tiltrotor) aircraft. The AHS proposal reports are generally limited in page count, causing the student teams to include the discussions that have the greatest impact on the design (engineering), and briefly discussing other topics (methodology, and intermediate results). This leads to a good presentation document, but does little to archive the complete design in a manner so that design data might be retrieved for future works.

The year 2001 project relied on two previous tiltrotor vehicle reports from 1997 (Close Air Support/Escort tiltrotor) [12], and 1999 (Uccello-civil aviation tiltrotor) [13]. These reports did not contain the complete versioned set of Requirements Data that would be sufficient to describe the vehicle configuration, and the associated decision making that led to that vehicle. This thesis is a re-visit of the 2001 project, using a digital form of the IPPD methodology integrated with a database acting as the Requirements data manager to archive the design and provide a template for future rotorcraft designs. It is the intention of this thesis to offer a solution to streamline future efforts of this nature.

Nearly all vehicle designs stem from the statement of a mission profile requirement. There were three mission profiles stated for the 2001 AHS RFP. The most important of which was taken to be the Search and Rescue (SAR) mission. This mission was to travel 300 nautical miles offshore to retrieve 2 victims from a ship in distress, during near hurricane force winds. The mission was made more difficult to achieve by a requirement to avoid mid-air re-fueling. All of the fuel necessary for the mission needed to be carried efficiently onboard. While the fuel tankage for the proposed Kingfisher design was carried primarily in the wing, provisions were made for additional below floor fuel tanks. Fuel carriage was seen as a high importance to the customer, by the team. Given the fate of the helicopter in the “Perfect Storm” movie crashing into the sea with

the crew onboard, this made good sense to the team. A graphic depicting the SAR mission profile is provided in Figure 2.2.

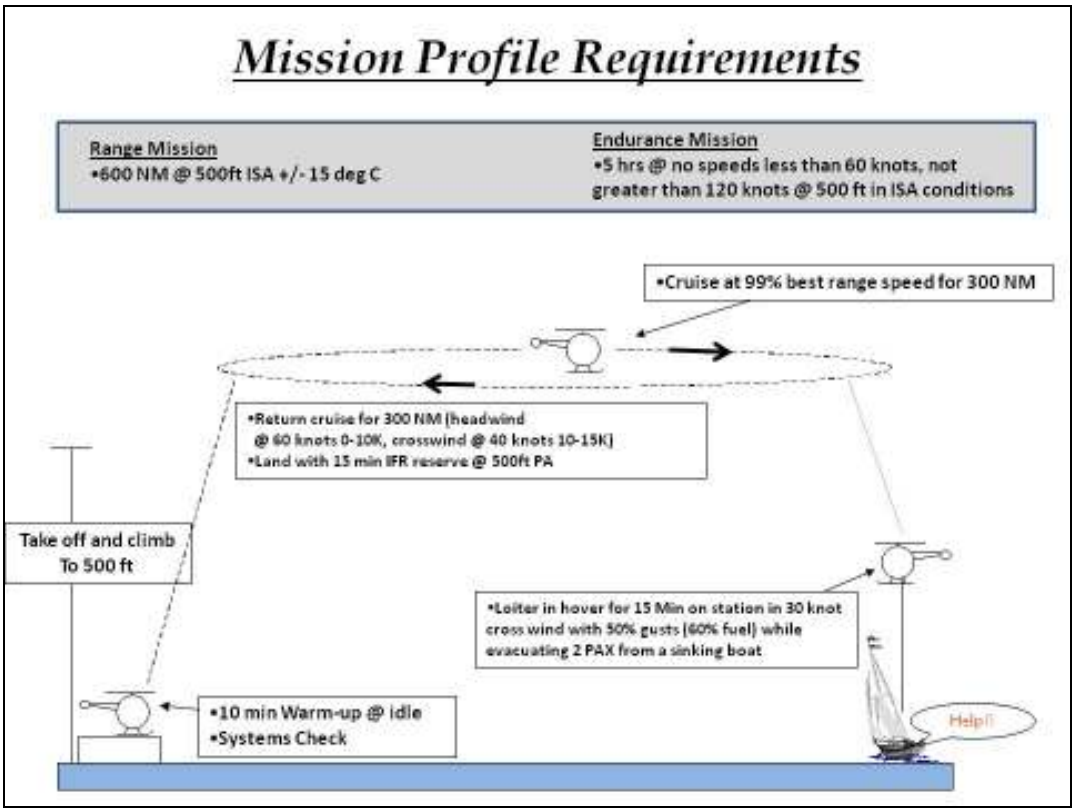


Figure 2.2: 2001 AHS RFP Mission Profile Requirements [14]

The graduate student Integrated Product Team developed a proposed vehicle concept called the "Kingfisher". A depiction of the Kingfisher vehicle is shown in Figure 2.3.This vehicle design met or exceeded all of the Customer Requirements dictated by the AHS RFP. Several aspects of how the overall design met the RFP requirements are of particular importance to this thesis.

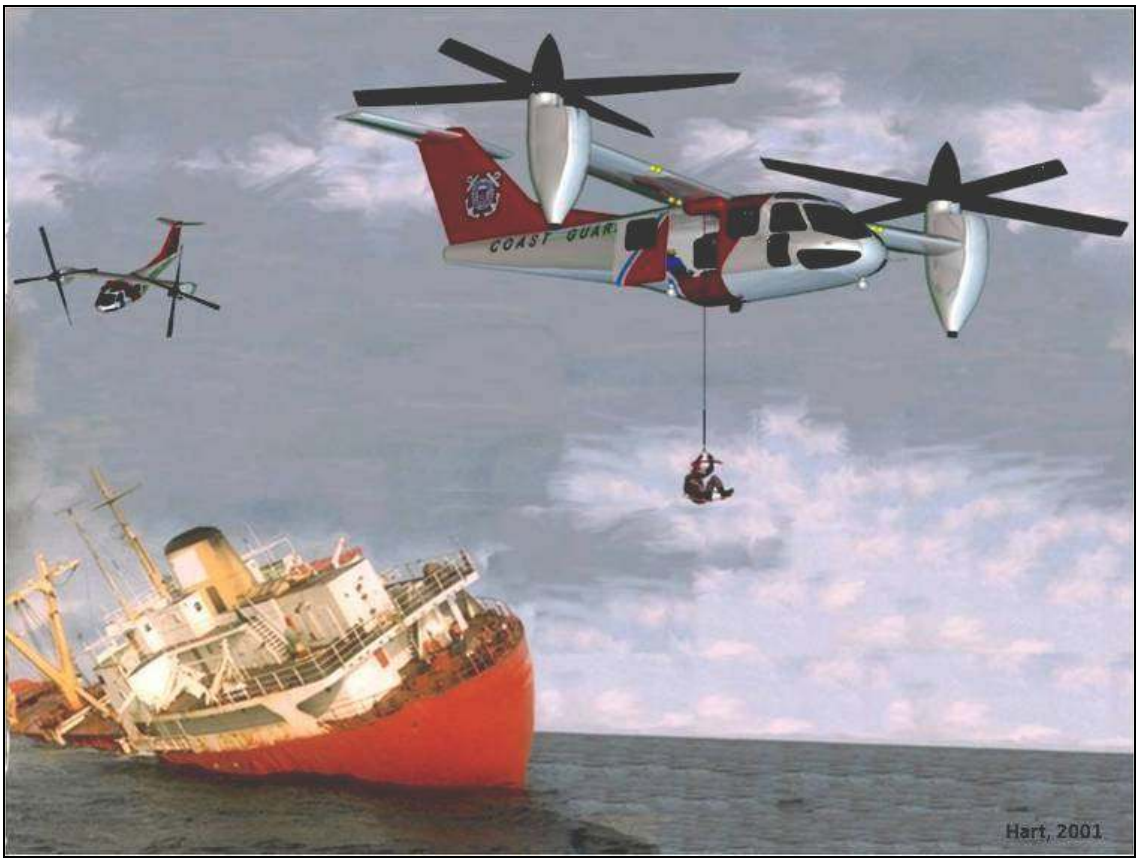


Figure 2.3: A system depiction of the Kingfisher Advanced Technology Search and Rescue Rotorcraft, capable of performing the "Perfect Storm' mission. From the cover of the 2001 GT Proposal to the AHS Committee. Hart, 2001. [15]

Initial Requirements Analysis

In the fall semester, a sub-group of the graduate team began to look at the AHS RFP. They performed a complete review and Systems Engineering analysis of the requirements. The sub group concluded that the best vehicle configuration was a single main rotor vehicle, similar to the UH-60 Blackhawk. However, during the next (spring) semester, the total team reviewed the system engineering analysis, and changed the down selected vehicle configuration to a tiltrotor configuration. This situation is important for two reasons.

1.) Very often, the system engineering activity is repeated in its entirety, often more than twice. It is for this reason that the Requirements analysis tools and data need to be constantly retained in a useable format to support the rapid iteration of the systems engineering process whenever it is necessary.

2.) There was a need by the original team to have an improved access to legacy design information concerning the tiltrotor configuration. This was not generally available to the team, as stated previously. Had they been more aware of the unique ability of the unconventional tiltrotor configuration, they might very well have arrived at the tilt rotor decision during the fall semester, with no need for iteration. This shows the value of a design team having direct access to an archive of datasets generated by legacy design efforts, specifically the systems engineering analysis tools and data.

Propulsion Configuration

The tiltrotor configuration was a wise final choice for the graduate student team, based on the mission profile provided in the RFP. It was not initially obvious to the team that a Search and Rescue mission of the type depicted in the Perfect Storm movie depended on a vehicle that had high cruise speed, and heavy weather stability. This meant that the vehicle would be generally larger with more power required than a conventional design to provide stability and endurance in elevated storm force wind states. This would make for a fairly un-economical helicopter in normal operations, out of the storm wind speeds. However, the tiltrotor design afforded better fuel economy in the airplane mode, making it capable of the heavy weather scenario, while still remaining economical for "everyday use".

Indeed, the tiltrotor configuration tightly addressed the primary mission stated in the RFP, that of Search and Rescue. Conventional helicopter speeds generally top out at the 170 knots range. A tiltrotor, operating in airplane mode, is capable of 330 knots. There was a relatively simple but important question that was posed to the design team, at the time. The question was: "If you are injured, or lost at sea clad only in a life vest, at what speed to you want the air ambulance to come to your assistance?" The resounding response was "As fast as possible!! We should strongly consider changing to the Tiltrotor configuration…" In the end, the vehicle system engineering was worked through a second time, and the tiltrotor configuration down selected.

It is important to note that not all of the system engineering data created during the initial Kingfisher analysis (fall, 2000) was discarded. The tiltrotor configuration was decided instead of a conventional single main rotor, like the UH-60. In the final design, the geometric definition of the hull closely followed a proven vehicle design, the UH-60. The cockpit layout, nose, and cabin dimensions were all derived from the UH-60 Blackhawk vehicle. The wing, rotor pods, and empennage were all based on the successful XV-15 design. The entire vehicle was proportioned to fill a vehicle size gap between the larger V-22 Osprey and the smaller XV-15 designs.

Advanced Flight Controls

The customer requirement for the incorporation of advanced flight control technologies was a major part of the Kingfisher vehicle effort, even ahead of the CAD and computer aided analysis (CAA). This single aspect of the design was identified early on as the item of primary importance to the Customer. Even with this realization at the start of the project, the time spent in the identification of alternatives, and down selection

of a single architecture for the flight controls continued to the evening before the proposal report mailing. It was readily agreed by the team that they had identified a solid flight control system, if only they had a week or two more to further validate the system for the proposal. Several of the advanced technology candidates for the flight control system are depicted in Figure 2.4.

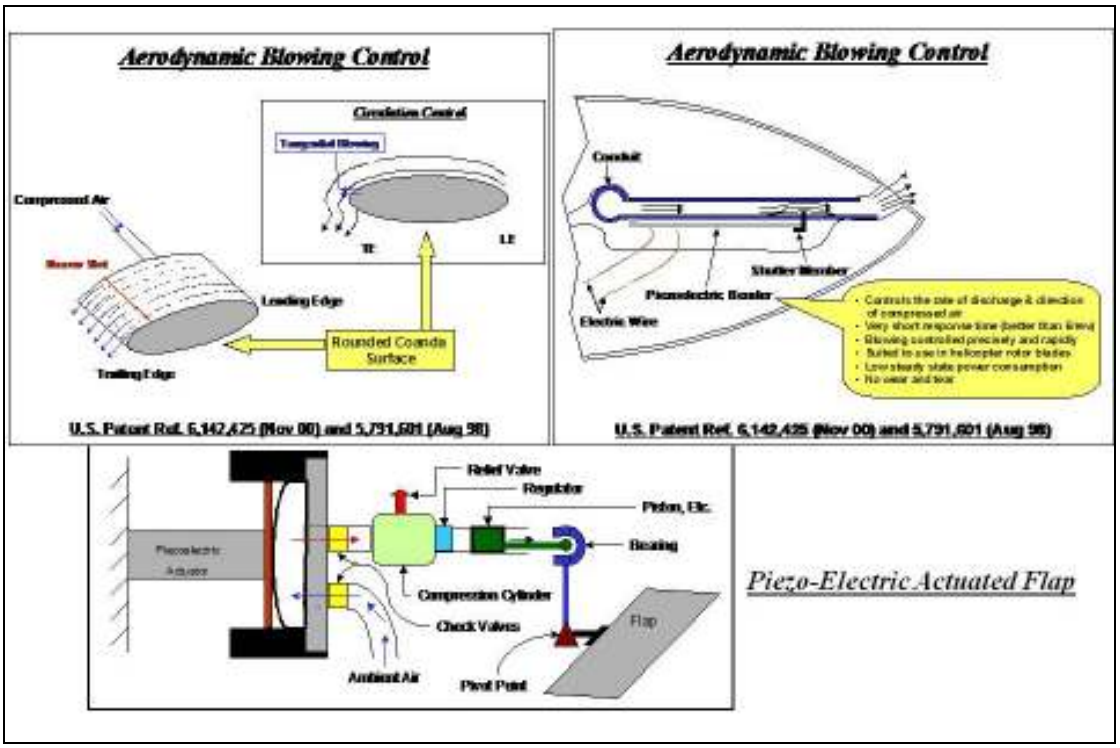


Figure 2.4: Technology candidates for implementation of advanced flight controls on the Kingfisher vehicle system. [14]

The lack of analysis time available for the flight controls system emphasizes the need to reduce the time associated with the consideration of the vehicle system engineering and analyses. The time saved would then be directly available to investigate the more difficult areas of the vehicle design. These areas are typically associated with the application of high technology, high risk, highly innovative solutions to design

challenges. High technology solutions typically exhibit low Technology Readiness Level (TRL) values, with an associated scarcity of information, including analysis data. It is hoped that the current thesis will provide an environment that will accomplish the following two goals:

1.) Reduce the time of systems engineering analysis for the IPT to be able to devote increased time to the definition and development of advanced technologies.

2.) Provide the beginnings of a Computer Integrated Environment where the descriptive and analytical data associated with advanced technologies can be archived through knowledge capture. The environment would ideally be used not only for the organization and capture of knowledge, but also for distribution at the appropriate time-during systems engineering, to the appropriate subject matter experts engaged in vehicle design.

The combined use of the 2001 AHS RFP and the associated Kingfisher vehicle works well to illustrate the proposed Computer Integrated Environment, as will be shown in subsequent chapters of this thesis. It provides for a generally successful legacy design, featuring the introduction of innovative technologies on a number of levels, including the tilt rotor, and flight control sub-systems. The vehicle was chosen partly because it was a legacy vehicle concept. The choice of this design removes the thesis from the constraints often imposed by the timelines of an active project. Instead, the vehicle design methodology and specifically the system engineering methods and tools are considered carefully, offline, so that they might be introduced in an appropriate manner to the overall design methodology of any IPT effort. This could be taken to include a re-design of the Kingfisher, once the environment is proven out, and a template created for future work.

The Kingfisher vehicle concept is still relevant today. Sadly, there is no similar vehicle currently on the market that can perform the "Perfect Storm" mission. Perhaps the Kingfisher design concepts should be revisited. Regardless, the development of a Computer Integrated Environment that facilitates the reduced time and cost of design and increases quality due to the availability of that time will surely save more lives than a Kingfisher vehicle in the long run.

CHAPTER 3

REQUIREMENTS DATA MANAGEMENT

System Engineering is used to coordinate the early development of aerospace vehicle designs through operation on customer requirements to synthesize product systems. A formal definition of Systems Engineering states: “System Engineering is an interdisciplinary approach to enable the realization of successful systems by focusing on customer needs and required functionality early in the development cycle, then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.” [16] INCOSE, 2008

The Systems Engineering process can be generally visualized through the graphic depicted in Figure 3.1. Through the Conceptual Design steps defined by Dieter [17], many of the systems engineering best practices are employed to define a quality product that meets or exceeds the expectations of the customer. Unfortunately, the process defined by Dieter was conceived before the widespread use of the digital computer.

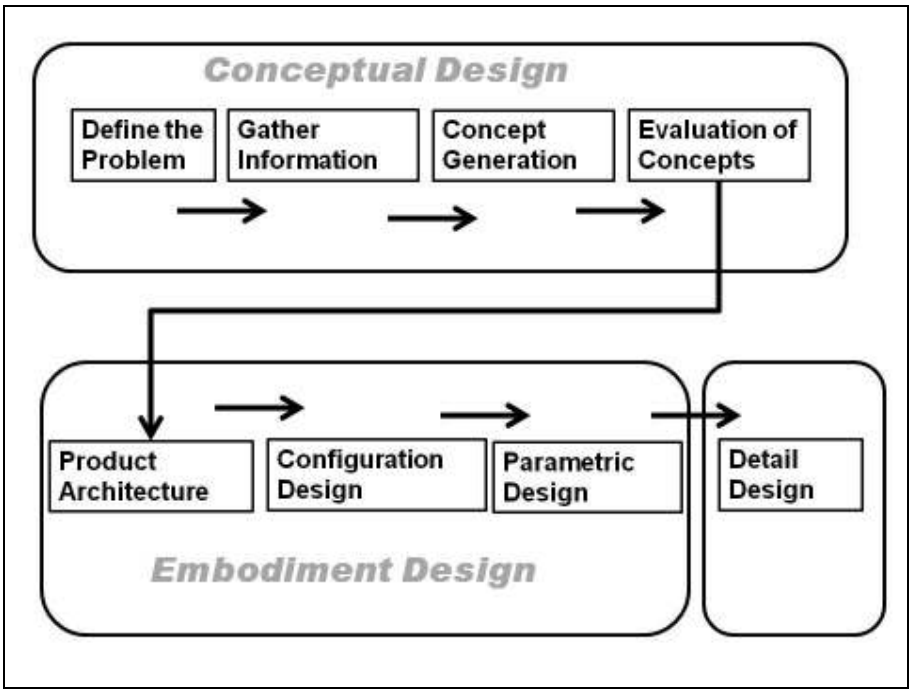


Figure 3.1: "Discrete steps in Engineering Design Process from Problem Definition to Detail Design." Dieter, 2000 [17]

There is a modern need to revisit the processes defined by Dieter in the context of digital computers in the modern Information Age. There is an opportunity to define the IDE for the modern conduction of engineering design, specifically systems engineering. The IDE is a relatively new term to describe a representative digital data based file system residing on a computer somewhere. The integrated term implies that the collection of files will be compatible with similar systems located on similar computers. Ideally, this represents a database that is accessible globally through the internet, providing roles based controlled access to specific data sets.

Modern DoD Defense System Acquisition policies actually mandate the deployment and use of an IDE for modern weapons systems. This is evident from the extraction from the Broad Area Announcement for the Broad Area Maritime Surveillance (BAMS) program, shown in Figure 3.2. The BAMS program is an unmanned, long

endurance flight vehicle system for the United States Navy that is currently in the SDD phase.

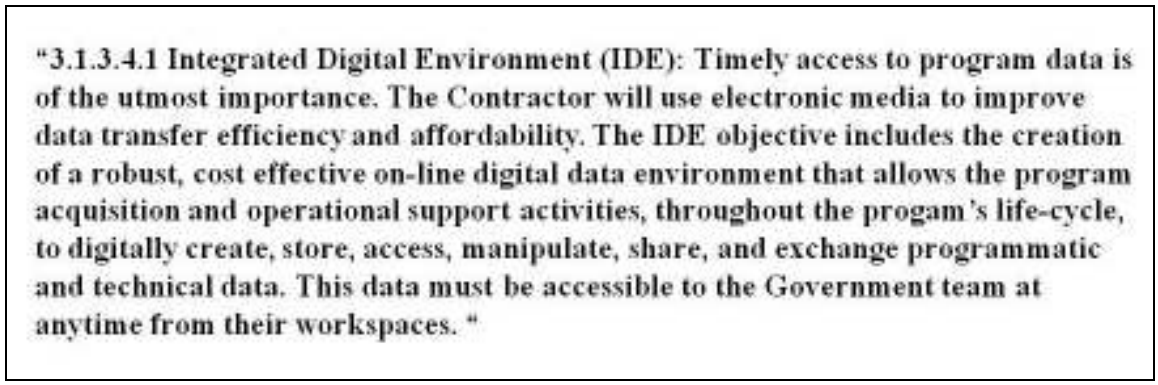

"3.1.3.4.1 Integrated Digital Environment (IDE): Timely access to program data is of the utmost importance. The Contractor will use electronic media to improve data transfer efficiency and affordability. The IDE objective includes the creation of a robust, cost effective on-line digital data environment that allows the program acquisition and operational support activities, throughout the progam's life-cycle, to digitally create, store, access, manipulate, share, and exchange programmatic and technical data. This data must be accessible to the Government team at anytime from their workspaces. "

Figure 3.2: Broad Area Maritime Surveillance (BAMS) Broad Area Announcement (BAA) out take stating the requirement for deployment of an Integrated Digital Environment (IDE). [18]

Modern conceptual design of complex systems calls for the concurrent consideration of both the Product and the Processes associated with the product. This is a direct result of the quality revolution, which started in Japan in 1970's in response to the situation depicted in Figure 3.3. The resulting Integrated Product and Process Design methodology allowed for the elimination of disciplinary "stove pipe" design organizations. They were replaced by IPT comprised of Subject Matter Experts (SME). Involving representatives from the multiple disciplines of design and manufacturing brought forward to the conceptual design phase many of the decisions that resulted in costly re-design, if identified later in the product development. The Systems Engineering process that has been in place for 20 years has incorporated the integrated product team into its Best Practices.

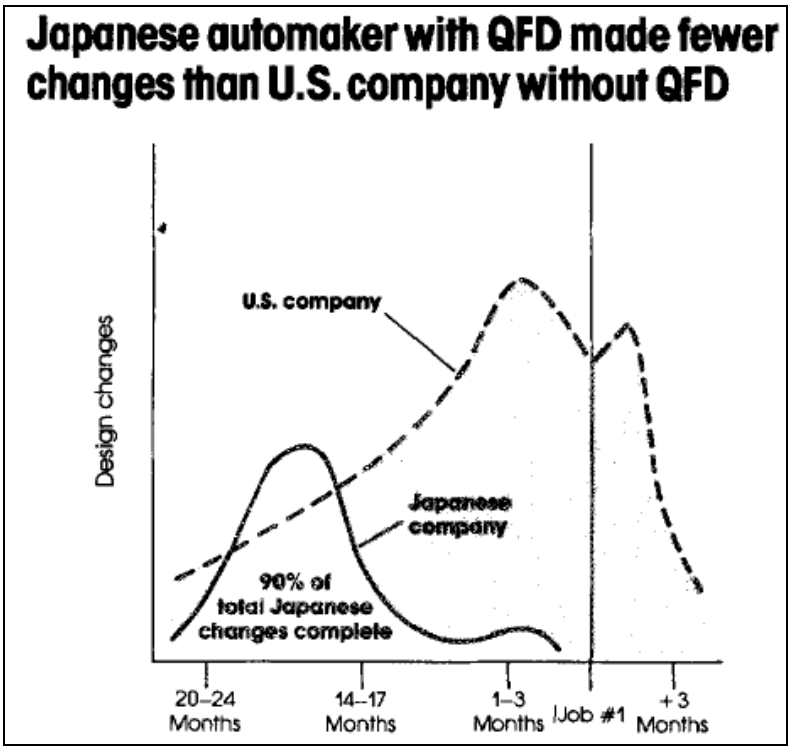


Figure 3.3: Design Changes vs. Time Source: "The House of Quality" Harvard Business Review [19], [20]

Looking at IPTs from another point of view, one could state that the new methodology brought forward all of the hard decisions to the conceptual design team and made their work more difficult, with increased data volumes to consider. Avoiding a debate on the plight of systems engineers worldwide, it is sufficient to note that integrated product teams have been shown to produce higher quality products with fewer defects. This effect was most evident in the automotive industry in the 2000s, where production lead times dropped to 18-24 months. This is in stark contrast to the aerospace industry where production lead times can be as long as 15 years, and the effects are less apparent. Current DoD acquisition reform sets target cycle time values at 5-7 years from program launch to production. [4]

While quality improvement was achieved, it remains a fact that the system engineering effort has increased substantially, with little additional time allotted to the activity for the increase in work. This creates tremendous pressure on the IPT to be efficient and mechanical in their processes of considering viable designs featuring mainstream technology alternatives. There is very little benefit to a team that "shoots for the sky" in terms of product integration of multiple low TRL technologies, only to be severely reprimanded for spending an extensive amount of time to develop them. The need to develop new technologies into product designs will never disappear. Common solutions to this dilemma are to implement medium risk level technologies at a one- or two-per product rate. However, this is a compromise at best. Modern products achieve market dominance through the implementation of cutting edge technologies while maintaining first-to-market status. It would be most beneficial to achieve the deployment of high risk technologies in greater numbers through increasing the time available for consideration of these issues. Given the static nature of product development and marketing deadlines, this hints at the reduction of time in other areas, to accommodate the increased time for TRL increase.

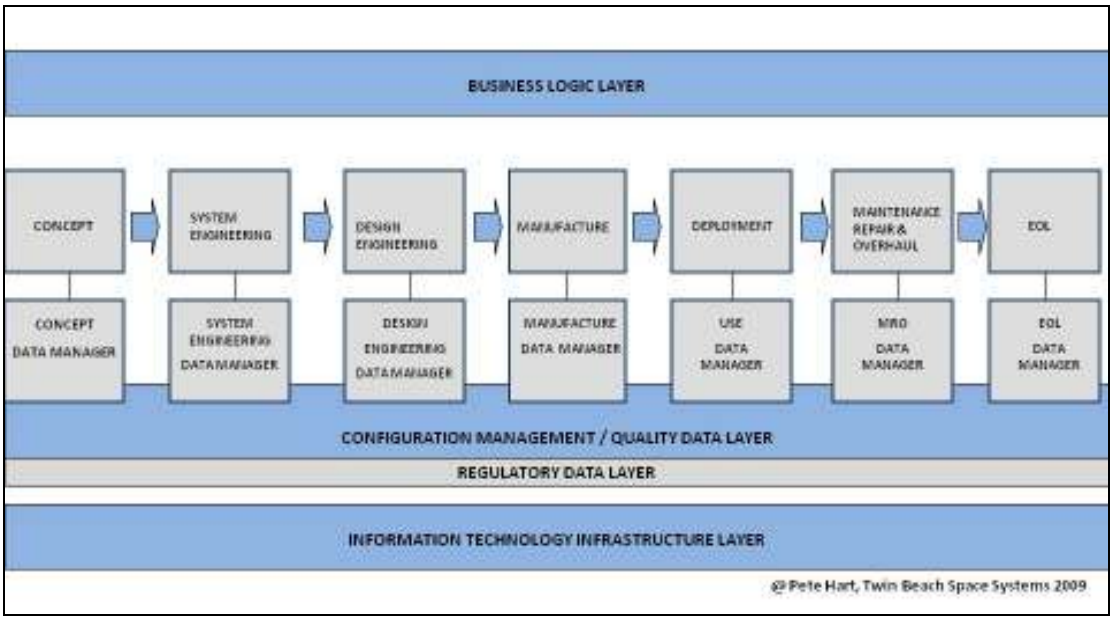


Figure 3.4: A Generic Product Life Cycle. Hart, 2009. [21]

The generic Product Lifecycle chart, depicted in Figure 3.4, exhibits a central spine composed of the general phases through which a product passes, as it enters and ages in the marketplace, eventually retiring. A modern age component is associated with each lifecycle phase- a Data Manager. The role of the data manager is to provide residence to the data necessary to conduct the activities of the lifecycle. In the case of the "Manufacture" phase, the manufacturing data manager retains the Engineering Bill of Materials (EBOM) which is used as a core for the creation of a Manufacturing Bill of Materials (MBOM) [23]. The EBOM is not created in the manufacture data manager, but a copy of it is located there out of necessity. The EBOM, created in the engineering data manager, in reality is a validation of the Requirements data residing in the System Engineering Data Manager. This type of relationship also exists for the additional lifecycle phases data managers. In this manner, the downstream lifecycle phases consume the physical architecture output of the Systems Engineering Phase. It is for this reason

that this thesis focuses on the Requirements Analysis performed in the Systems Engineering phase of the product lifecycle.

Product data flows through all of the product lifecycle phases, generally from a left to right manner in Figure 3.4. We can also see in the chart that each of the data managers is embedded into the Quality layer, which has responsibility for management of the product configuration, through change management to insure quality in all life phases. Directly associated with the Quality layer is the Regulatory Data Layer. These two layers are closely aligned, due to the fact that data generated to satisfy product regulatory interests of all kinds, must be approved by the Quality group, and related to a specific configuration data set (Version).

Product data flows through all product lifecycle phases. A single intact configuration dataset must be created and maintained. The configuration will flow from the point of definition and validation (System Engineering) to all other lifecycle phases. This will insure synchronized distribution, and in-context consumption of the as-engineered product data. A graphical representation of this concept is provided in Figure 3.5.

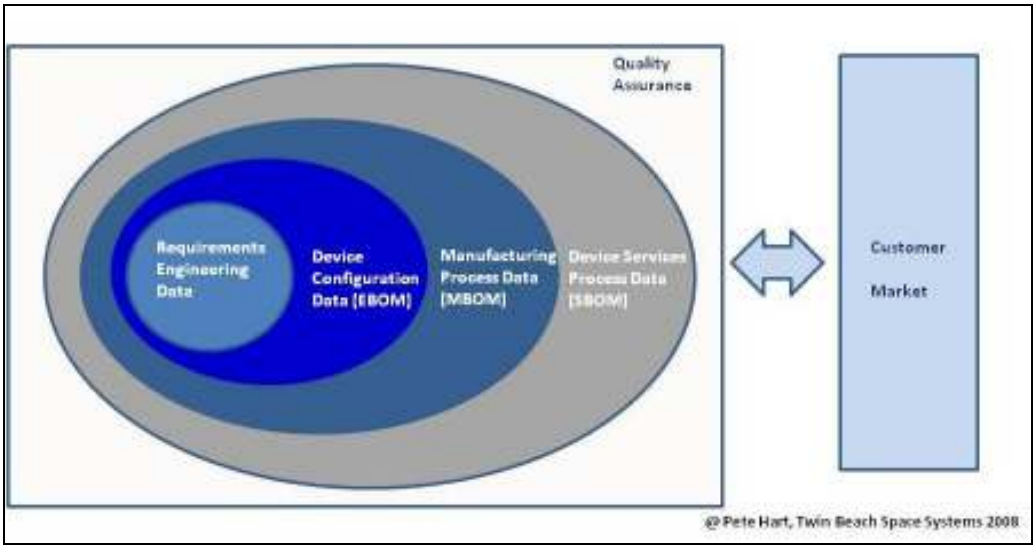


Figure 3.5: An "Egg Chart" showing the consumption of Requirements Engineering. *"Real Device Quality is contained within the Virtual Device Data, defined in the Requirements Engineering Environment, and detailed in the Engineering Bill of Materials (EBOM). By providing a methodology for management (distribution and consumption in context) of a single, intact virtual configuration data set, high as-engineered quality levels can be maintained and verified, throughout the downstream lifecycle phases of the real device."* Hart, 2008. [1]

In order to maintain quality at all lifecycle phases of the product, while also complying with all regulatory interests, a single intact configuration dataset must be created and maintained. The configuration will flow from the point of definition and validation (System Engineering) to all other lifecycle phases. This will insure synchronized distribution, and in-context consumption of the as-engineered product data, as derived from the requirements data sets.

With the advent of the personal computer, the methods of Systems Engineering became more manageable, due to the emergence of standalone tools to list and sort requirements. The text: "Engineering Documentation and Control-Practices and Procedures" [24] lists no fewer than 20 such tools in 1995. The number of these tools to accomplish a single common methodology suggests the inefficiency associated with

software development of the day. Many of these tools were standalone tools that did not communicate with other similar or complementary tools by design. It is for this reason that many of these tools still exist, although primarily to support portions of legacy products from years long gone. Generally, these standalone tools are phased out at the same time that the veteran knowledge workforce retires. In addition to being difficult to use, expensive to deploy and maintain, they were very difficult to learn for new users.

The large majority of these systems engineering software were basically document management systems. They were developed to track and retrieve text based documents according to name, date, or author. They were generally command line driven, as helpful graphical user interfaces were non-existent at that time. In addition, graphical capabilities were kept to a minimum due to the lengthy time necessary to display charts and graphs. There was a need to develop a new generation of software based on the maturity of the personal computer.

There have been numerous tools developed recently to address the modern computerization of processes related to the design engineering of Aerospace Vehicle Systems. Originally, Product Lifecycle Management tools were created specifically for the Aerospace Industry in the late 1960's. The modern PLM tools have recently found more widespread use in the full spectrum of product manufacturing disciplines "Product Life Cycle Management is the evolutionary process to seamlessly integrate all information domain application functions supporting all cross-disciplinary life cycle processes to achieve significant corporate productivity gains and competitive advantage." [22] Teamcenter Systems Engineering (TCSE) is a modern PLM component tool for

satisfying the challenge of creating a Computer Integrated Environment for Systems Engineering.

TCSE is a new version of one of the legacy systems engineering software tools formerly known as “Slate” and “Teamcenter Requirements” [25]. TCSE is produced by Siemens PLM Software [26]. The Teamcenter family of tools has been chosen by Siemens as the platform to be developed into a totally integrated suite. Siemens goal is to provide seamless data transfer between all of the data managers depicted in Figure 3.4. In this thesis, focus is placed on the Teamcenter Systems Engineering software environment as one possible solution to the early issues related to systems engineering software and methods.

TCSE [27] is available from Siemens as a standalone PLM tool. Recently, Siemens PLM Software began porting TCSE as a module of the Teamcenter Unified architecture. Due to software development schedules and maturity, the standalone tool will be deployed and discussed here. TCSE as a standalone tool is based on the Versant database software and features a Java based web interface. The software architecture of TCSE is shown in Figure 3.6. For the purposes of illustrating all of the concepts associated with a digital systems engineering methodology, the complete TCSE software was installed and basically configured to default settings according to recommended out of the box specifications. This was done to insure that the basic functionality and methodology of the thesis could be duplicated at any time.

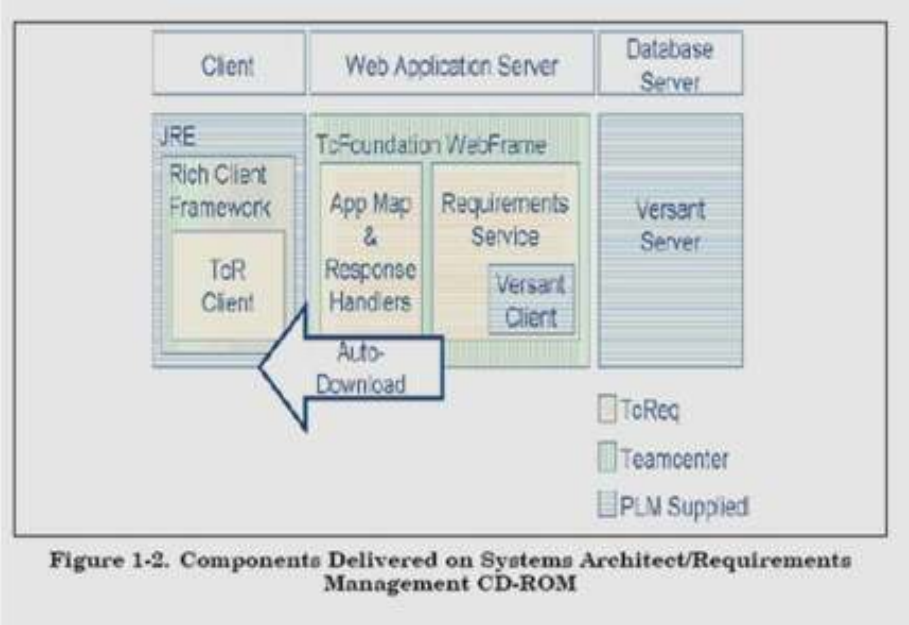


Figure 3.6: Teamcenter Systems Engineering Software Architecture, Siemens PLM Software, 2009. [28]

The entire installation process for the proposed Integrated Digital Environment is quite complicated, tedious, and not for the faint of heart. There are numerous component tools that must be installed as pre-requisites for TCSE installation. A graphical depiction of the software infrastructure used in the thesis investigations is presented in Figure 3.7.

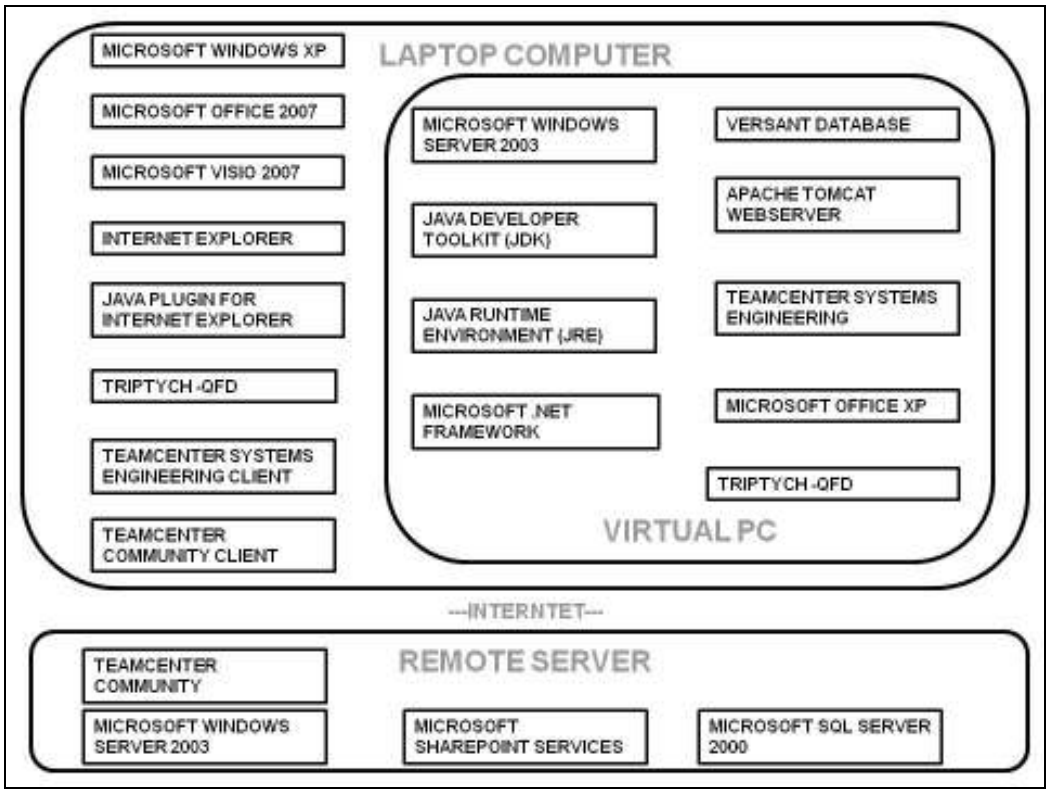


Figure 3.7: Teamcenter System Engineering Software Component Installation methodology. Siemens PLM Software, Hart, 2009 [28]

Note that the use of a Virtual PC Image was extremely useful in hosting the TCSE environment. The Virtual PC basically allowed the entire TCSE software environment to be duplicated and versioned during successive failures and successes during installation. The Virtual PC was installed on a single 250 Gigabyte USB hard drive and accessed using the internet through a loopback adapter installed on the laptop computer. In general, performance issues were minimal even though the laptop was effectively running two distinct operating systems: Windows XP on the laptop, and Windows Server 2003 on the Virtual PC.

TCSE features two main areas of functionality. The first is an "Administration" area, where projects are created and users are added to the projects. Customizations to

TCSE can also be made in the Administration area. In general, this is an area of use by project administrators, but not by the team of subject matter experts. While essential to the operation of TCSE, the functionality of the Administration area is not primarily relevant to this thesis. A screen grab of the TCSE Administration area is shown in Figure 3.8.

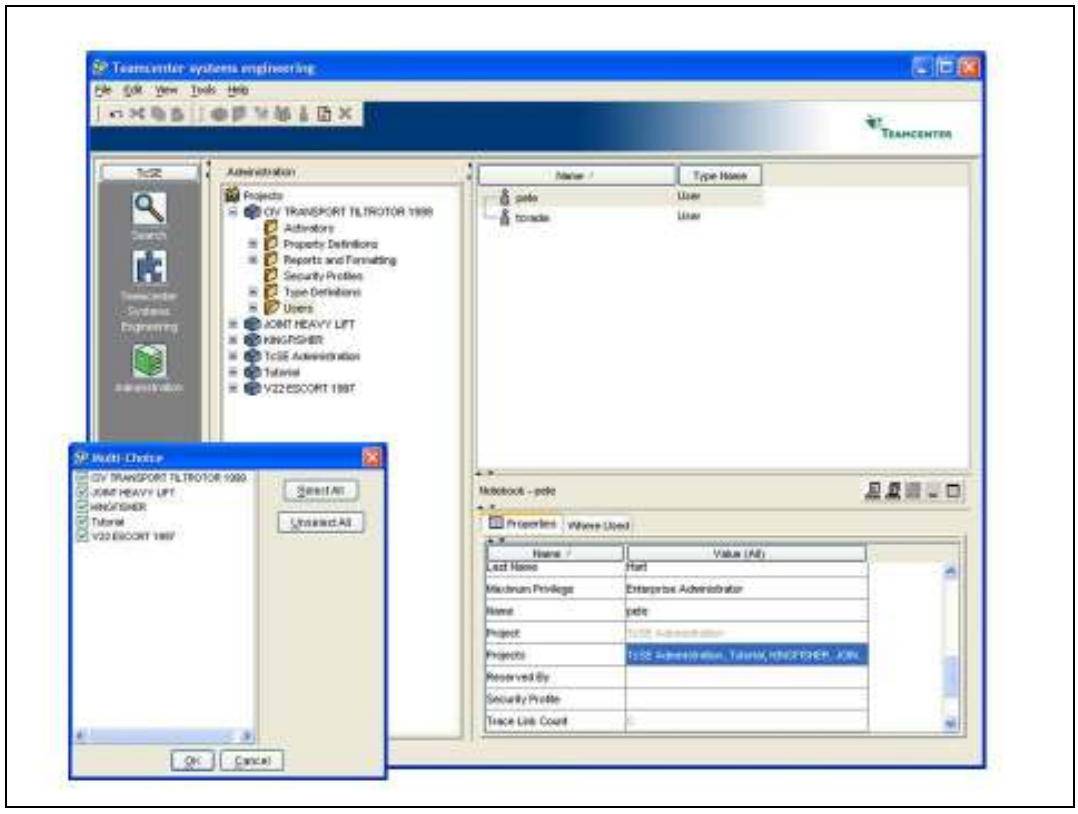


Figure 3.8: Image of the TCSE2007 Administration area. The screen grab depicts projects assignment to the user role. Hart, 2009.

The second area is called basically "Teamcenter Systems Engineering." This is the main operations area for all TCSE users. It contains the majority of the functionality related to requirements authoring, configuration management, change management, search, and logical linking. A screen grab of the graphical user interface for the TCSE user area is shown in Figure 3.9.

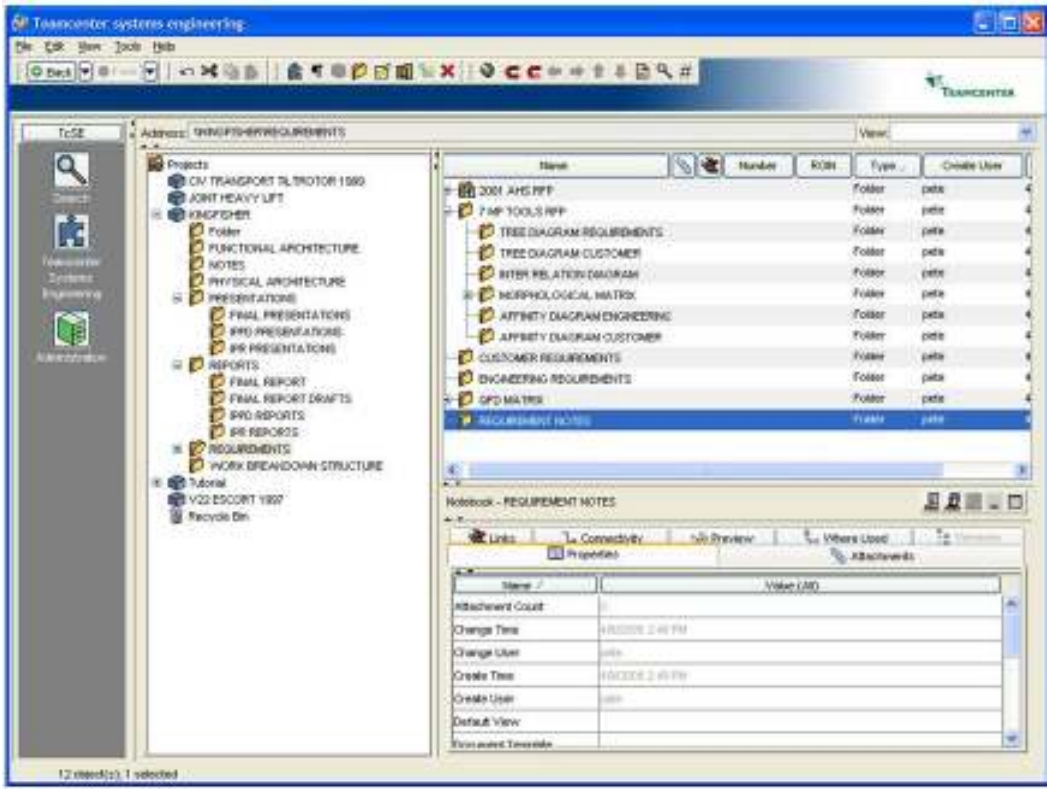


Figure 3.9: Image of the TCSE2007 Teamcenter Systems Engineering Project/User Area.

The TCSE GUI is composed of several windows, in strong similarity to MS windows look and feel. This is interesting, given that the entire tool is a web-based interface to the database residing on a remote system. The GUI presents the user with an immediately recognizable layout, where tools are predictably placed. Nearly all functionality is accessed through the Microsoft style pull down menus and the function buttons directly below them. This leaves a tremendous amount of room available for navigating the database.

The main window on the left is used to display the product data structure, arranged in folders. The folders may look like Microsoft Windows [29] folders, but they operate only as data containers in the TCSE database. The folders allow easy navigation to the requirement s datasets. Individual data items are displayed in the upper of the two

rightmost windows. The column names at the top of this window can be easily customized based on user preferences which can be saved on a role by role basis. This addresses the fact that there are distinct differences in data interest, and use among the subject matter experts who will operate on the data. The goal of the software use is to: "Provide the correct information to the correct people at the correct time." The lower window on the right is used to display the details of the requirements data sets. This could include the display of the text of the requirement, attached notes, trace links, and where used. Search queries are made using the dedicated Search function located on the far left of the screen.

The standalone TCSE environment is a Java [30]-based web application. The GUI depicted in Figures 3.8 and 3.9 are actually the local client software, accessing the Versant [31] database through a web application server. In the case of TCSE, several different web application servers may be selected by the system administrator. For the purposes of illustration for this thesis, the Apache Tomcat [32] web application server was deployed. Apache Tomcat is a "pure Java" http webserver environment for Java code to run on, developed by Apache Software Foundation.

The basic function of the TCSE software is to manage the data associated with requirements, and their analysis to create a physical architecture. The co-location of requirements and output from diverse analysis tools alone will not speed the process of systems engineering. There is a need to reduce the waste associated with the traditional system engineering activities. This is accomplished in TCSE through the implementation of two main themes: Configuration Management and Product Change Management.

Configuration Data Management is achieved in TCSE through the residence of requirements data and the interactivity of IPT members to that data. The management of this data is critical to insure that all of the team members are working on the current version of the requirements dataset. Versioning of both the entire requirements project dataset and individual requirement items in the database accomplishes this. Even small incremental changes to a single requirement can have a drastic effect on the output of the analysis tool suite which is operating on that requirement. Configuration management insures that the analysis tool suite is using the latest requirements data and that they are collectively versioned together as a requirements project dataset.

In order to efficiently implement configuration management in TCSE, there must first be a configuration. The issue of Product Data Structure is not a trivial issue when dealing with engineering databases such as TCSE. Without the imposition of a logical and navigable product data structure scheme on all users, the database would quickly become clogged with data and impossible to use. [33] The concept of developing a unified set of Product Data Structures has been considered as a high priority since the 1990's. Several are currently being developed.

One such major effort is being promoted by the US Department of Defense as the Department of Defense Architectural Framework (DoDAF). The DoDAF [34] effort is aimed at providing a common product data structure primarily for weapons systems, across all of the armed forces including joint forces. While the development of DoDAF is at the cutting edge of Defense acquisition reform, there is insufficient space to discuss all of its merits and strategies. For the purposes of this thesis, DoDAF is a much more complicated approach to product data structure than can be addressed in an illustrative

manner in the current research. It is important to note that Siemens software developers are currently making accommodations for DoDAF to be integrated into the core functionality of the TCSE environment. This will bring TCSE into direct alignment with a US government mandate for the application of advanced systems engineering tools to streamline defense systems acquisition business processes.

"All major U.S. Government Department of Defense (DoD) weapons and information technology system acquisitions are required to develop and document an Enterprise Architecture (EA) using the views prescribed in the DoDAF. While it is clearly aimed at military systems, DoDAF has broad applicability across the private, public and voluntary sectors around the world, and represents only one of a large number of systems architecture frameworks."

Table 3.1 – DoDAF mandated requirement to use an Enterprise Architecture for weapons and information technology acquisitions. [34]

For the purposes of this thesis, a logical and navigable product data structure has been implemented based on historical vehicle proposal development within the graduate teams at Georgia Tech Aerospace Engineering. The structure provides for a folders based arrangement of the requirement items. It also provides a flexible system for the incorporation of non-requirement data into the database environment. The example Product Data Structure of the Kingfisher vehicle project in TCSE is shown in Figure 3.6. It is believed that this product structure meets the needs of the example investigation; however, there may be room for improvement on many levels. There is certainly a

caution against the adoption of the presented product data structure without a bit of contextual consideration beforehand.

In TCSE, the product data structure is maintained through configuration management by user roles assignment. Typically, the roles for a single typical Requirements project are a single TCSE project administrator and multiple project team members. A separate Enterprise Administrator is necessary to oversee the entire TCSE environment for all projects; however, this role would rarely interact with the IPT, if at all. Each of the user roles are assigned access permissions based on their function within the IPT. Permissions of read and write are typically assigned to the team members, with delete privileges reserved for the project administrator.

In TCSE, it is possible for a role to be created for a person or group that is not a direct participant on the IPT. This is beneficial to provide project transparency to an engineering or business manager that provides oversight to the project. Perhaps less obvious is the ability to permit limited read access to TCSE datasets by external groups. This would be beneficial to the "contracting authority" or a "program sponsor" to be able to have daily updates to the activities of the Integrated Team. An opportunity for a substantial reduction in time and effort can be realized through this setup.

The major stakeholder(s) is granted immediate access to a limited subset of the data to provide decision making support, at any point in time. This reduces the emphasis on the conduction of Intermediate Program Reviews (IPRs), (also known as Preliminary Design Reviews (PDR)) which consume large amounts of time for large numbers of people. Continuous stakeholder transparency to program data extractions and reports allows for direct collaboration with the team. Specifically, it helps to avoid the

embarrassing event of an IPR where there is a disagreement between the stakeholders and the design team on work to date. This is a common occurrence in the development and design integration of cutting edge technologies with low TRL values. The occurrence of that situation points out the waste in the system engineering process that can develop as a result of a disengaged stakeholder. The work will have to be reviewed by the team, and solutions generated to the satisfaction of the contracting entity, wasting valuable time and effort.

The example TCSE environment for the Kingfisher project was augmented through the creation of roles to address this situation. The roles of "AHS Rep" and "Boeing Rep" were created to give the two major stakeholders access to the environment to achieve the necessary transparency. (Boeing Rotorcraft Systems was a corporate sponsor of the 2001 AHS Graduate Design Competition.) It is not suggested that these stakeholder roles be given total access to the requirements data set. It would be more prudent to provide limited access to a subset of the datasets, specifically tailored towards the sponsor interests. These would include draft IPR presentations, auto generated progress reports, and baseline assumptions.

Product Change Control is achieved in TCSE through the implementation of an authoritative approval process. This restricts the ability by team members to over write existing requirements data without the approval of an individual or committee. The commonly accepted method of implementing change control is by accumulating change requests for a period of time so that they may be approved as a group. This forms the triggering basis of the versioning process in TCSE. Industry-based software development requirements would commonly be updated and versioned monthly. But given the short

span of the systems engineering phase of aerospace design, the update and revision rollouts would need to be accomplished more frequently, on the order of days.

In the event that a data conflict should arise outside of the Revision process, TCSE incorporates an Audit trail. This file is created automatically, and recreates all of the TCSE authoring and change activities in sequential order. The file is used in case of emergency, generally to retrieve some sense of data status at the time of a database failure or software update. In general, the audit file captures who did "what" to "what data" at which point in time.

There is insufficient space in this thesis to list and describe all of the functionalities of TCSE. However, it is important to describe several fundamental functionalities, in preparation for discussions on the use of the tool. A few of the more heavily used and significant functionalities are described, based on their contribution to the example overall systems engineering project.

Import/Export of TCSE Project

The Import/Export function is used on two very different levels within TCSE. The first use of the import function would be to introduce a previously created Requirements Project from an external TCSE source. Through this functionality, an entire project can be archived and exported from a given TCSE system and imported into a second TCSE system. The ability to archive a project using the export function is of primary importance, given the tendency for aerospace vehicle design concepts to fade in popularity and then re-emerge at some future time. The export function is fairly complete in the packaging of a TCSE project. The export function of an entire project will capture and transmit all of the following:

Folders	Requirements	Building Blocks
Groups	Notes	Diagrams
Properties & Values	All Schema data	Parent/Child/Sibling relationships

Only Trace Links between objects within the project will be exported. Trace links to database items outside of the given exported project will not be captured.

The above listing contains nearly all of the data associated with a project in TCSE. One of the primary goals of this thesis was to develop a capability and methodology for knowledge capture, management and distribution to reduce the time to consider vehicle design concepts. The Import/Export function accomplishes this by packaging the entire set of vehicle design concept systems engineering (including all analysis tools and output) for distribution to other groups of designers at some point in time. The project export becomes a template that can be used by any other team investigating a similar set of vehicle conceptual requirements. In the event that only minor excursions from the technology and layout of the vehicle are required, the exported project could provide the necessary systems engineering dataset intact, ready for subsequent small surgical changes. The suggestion of a Digital Legacy Data Repository as a library for the checkout and re-use of legacy TCSE projects is depicted in Figure 3.8. This methodology could save up to 80 % of the time associated with the systems engineering consideration of a vehicle design. Lesser percentages would be associated with larger excursions from the baseline template created by the original vehicle project export.

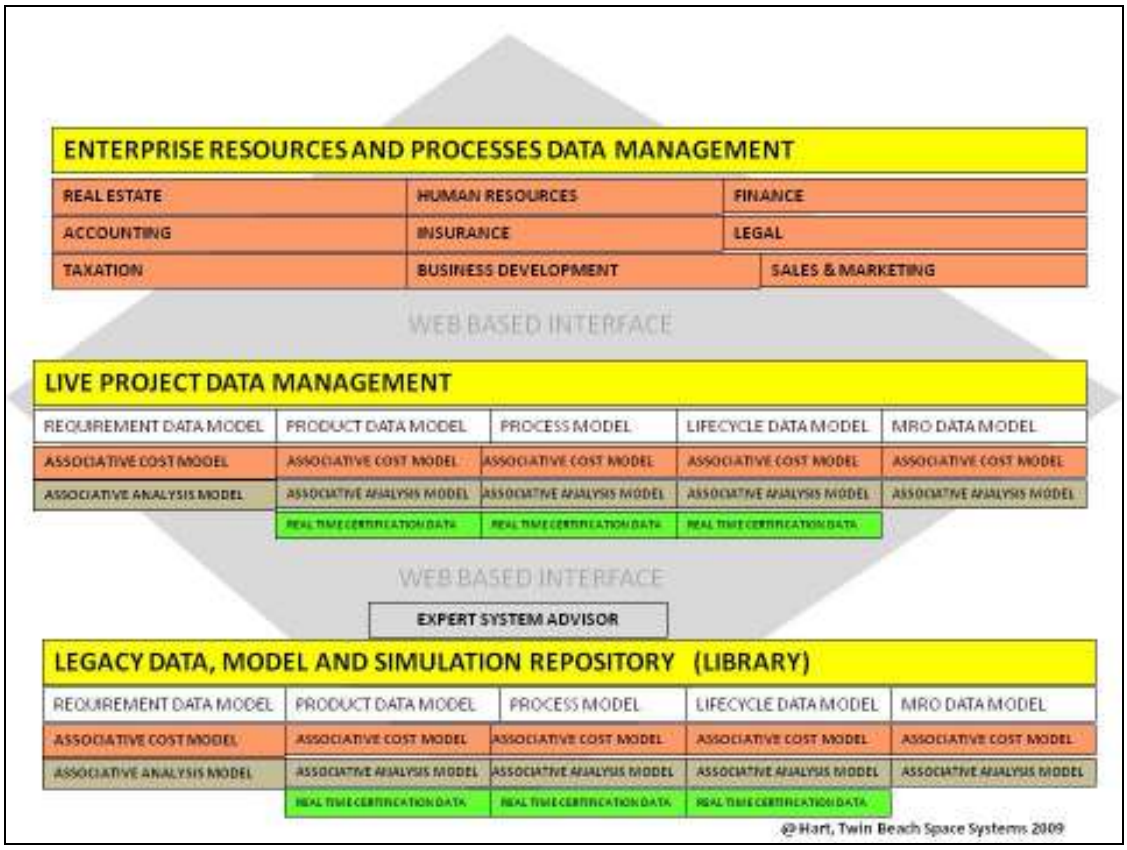


Figure 3.10. "A Digital Manufacturing Enterprise Data Infrastructure Configuration, featuring a Legacy Data Modeling and Simulation Repository (Library)". Hart, 2009 [35]

Import

The second usage of the Import/Export function is on a much smaller scale than exporting the entire project. It is possible to use the Import function to retrieve data from diverse external sources for introduction as TCSE data items within the database. This is a method to provide the automated importation of requirements from non-TCSE tools such as Microsoft Word documents, or Excel spreadsheets. The methodology associated with this level of the import/export function will be discussed in detail in Chapter 3.

Export

The Export function is also useful at this lower level of use in the automated population of Microsoft Office based analysis tools with requirement data items contained in the TCSE database. The automated population of diverse tools such as QFD method and the 7 MaP tools in this manner greatly increases data accuracy and reduces the time to create and conduct these analyses. The export function can be used to populate a diverse set of file formats, including Matlab, Microsoft Word, Excel, and Visio.

Search

The main user activity of TCSE use is the entry of requirements data items. However, a more heavily used function than data creation or Import is the Search Function. The search function allows for the retrieval of requirement data from every corner of the database. The search function can be fine tuned by an experienced user to retrieve a narrow band of data containing content of interest. The beginning user will find that searching for a broader spectrum of data items may produce more predictable results.

The search function in TCSE is unique, in that it features an advanced capability to perform keyword searches. Most common search tools retrieve items categorized only by title, date of creation, or author. The TCSE advanced search functionality allows for the search of document and requirement body text for keywords. This is extremely useful in most cases, due to the large volume of data contained in the database, and the fact that the keyword most likely is not contained in the folder name or document title. This improves the usability of the requirement data by the team, and reduces time through increased team productivity.

Trace Link

Possibly the second most often used TCSE function, other than search, is the Trace Link. This capability allows for the logical linking of database items so that they may be considered in context. Trace Links can be made between a variety of requirements data items, including customer requirements, engineering requirements, functional, and physical architectures. Multiple links may be accomplished in a one-to-many or many-to-many manner. Trace links may also be made between database items residing in different projects. However, Trace Links cannot be propagated between items in TCSE and items in MS Excel worksheets. Trace Links may be established among data within TCSE, and within data within the Excel Worksheet. However, Trace Links cannot be made between a start data in TCSE and a finish data in the MS Excel. Trace Link status for any individual data item in TCSE is displayed in the lower right hand window.

The trace links provide traceability among the requirements data sets, linking requirements with satisfying data, or simply associating an individual 7 MaP tool analysis with a grouping of customer requirements. In more advanced usage, the Trace link can be used to provide traceability between data contained in different databases such as Teamcenter Engineering [36]. The design engineering activity can be seen as the satisfaction of the requirements engineering activity, following directly from the down-selected architecture in a synchronized manner. Providing trace links across the system engineering and engineering domains is a powerful method of reducing the time associated with iterative design analysis.

However, the difficulty associated with implementing this level of linking stems from the fact that currently, TCSE and Teamcenter Engineering (TCENG) use different

databases. The TCSE standalone tool uses the Versant database. TCENG uses a variety of database options including, Oracle [37], and DB2 [38]. This situation is being resolved currently through the development of the Teamcenter Unified product, which will replace the Teamcenter Engineering Product Data Manager. Teamcenter Unified incorporates TCSE as a totally integrated module, greatly improving the creation of trace. The existing TCSE-TCENG trace link functionality is definitely an advanced functionality that is far beyond the scope of this thesis.

Attachments

Where a requirement may be ambiguous or easily misunderstood, it is necessary to supplement the requirement data item with additional material. This is accomplished in TCSE by providing the Attachment functionality. The attachment is created as an item in the database that is related directly to the requirement item. Alternatively, a text document containing 7 MaP [39] tool training might be attached to the instance of the 7 Map tool file, in the database. The attachment function is not restricted to attaching documents and graphics to a requirement data item.

Where Used

The key to using a large database tool to support decision making is to be able to navigate quickly among the diverse datasets. While the folders in the product data structure provide general guidance on data location, they are not sufficient as standalone direction signs. It is common for requirements to be linked in non-obvious ways within the database. This is perfectly “legal” and does not violate any standing best practices. The existence of these non-obvious links is of critical importance when it comes to

change management. If a requirement data item is used in several functional architectures, changing the data item would invalidate all of the dependent architectures.

It is for this reason that the "where used" function is located in a prominent position for easy access in TCSE. The "where used" function provides a graphical pop-up window that displays all of the parent-child relationships associated with the selected data item. These parent-child relationships would not be revealed through the use of any other function within TCSE. The search function may find related data items by name recognition, but there would not be any information displayed on the parent child relationships that have been established. The "where used" function provides a direct visualization of the impacts that a change will have, in advance of making that change. This predictive capacity is a valuable tool in being able to estimate the time to implement changes, in terms of scheduling modifications.

TCSE Data Types

There are a variety of data types in TCSE that are used to actually populate the database. These will be discussed in the hierarchical manner in which they would logically be created in TCSE. Each of these data types will be used in subsequent chapters to illustrate the utility of the TCSE tool in streamlining the systems engineering phase of rotorcraft vehicle development.

A Project is created by the database administrator to establish a workplace to contain all of the data related to a single systems engineering effort. The project creation is important in that role based access privileges apply only within the project to which they are assigned. Along the same lines, trace links, requirement items and architecture building blocks cannot span across projects.

Folders are used within the project to separate and categorize the data according to some logical product data structure. The example Kingfisher vehicle design data is organized in a manner that would be consistent to a student team performing an academic vehicle design. Folders can be nested to numerous levels. As general purpose data organizers, folders are generic, and not distinguished by the data that they contain. There is one type of folder as a default in TCSE, although this (and just about everything else in TCSE) is customizable by a database administrative role.

Groups are used to group a wide variety of data types within TCSE. A group is most commonly used with the accumulation of similar requirements. But the use of the group is not limited to the requirement items exclusively.

Items are used to contain the requirements. Items can be arranged in a hierarchical order, providing nesting, numbering and sub-numbering to preserve the organization established in the original requirement source. Requirement items are usually numbered and comprise the basic database data for TCSE. They usually contain a single line of text that is used to describe the requirement. There are a variety of requirement items available and additional types may be created by the project administrator as needed. Examples of Requirement items are: customer requirements, engineering requirements, derived requirements, regulatory agency requirements, disciplinary requirements, etc.

Paragraph items in TCSE are used to supplement the use of the Requirement items when the requirement text has not yet been authored. The paragraph can contain any text. It is commonly used to represent the requirement item in raw form from a document source, before it can be distilled into a formal requirement statement and assigned as a Requirement item.

Trace Links, as described in detail above, provide traceability among the data within a given TCSE project.

Building Block items are used to represent the individual components of the functional architecture and physical architecture, and work breakdown structure. The building block is separate from the requirement item type in terms of underlying data content.

It has been discussed in this chapter that the TCSE tool is useful in creating an effective computer integrated environment for the systems engineering phase of an original PLM-Enabled Design Methodology. The functionality of the tool has been discussed with implementation and example shown in detail in subsequent chapters. The data types contained within TCSE were introduced to support the population of the database with the vehicle concept data to illustrate the methodology.

The TCSE functionality and data types described in this chapter form the basis for the proposed CIE for Systems Engineering. In future chapters, TCSE CIE use will be explored through example in the context of an IPPD methodology.

CHAPTER 4

CUSTOMER REQUIREMENTS

Before there can be a discussion concerning the satisfaction of customer requirements, there must be an identification of the customer. The customer is defined as the primary stakeholder in the vehicle design effort. But this primary stakeholder may change, depending upon the level of participation by the sponsor. For example, Boeing was the corporate sponsor for the competition which instigated the Kingfisher design. However, as a Maritime-based Search and Rescue vehicle, the United States Coast Guard could have been the customer, as they would purchase the system. The pilots could have been the customer as well, as they were the ones to actually have to safely fly the system. In addition, the survivor that was rescued could be considered a customer. Which one is the real customer?

In reality, they are all customers. There is emphasis on the primary purchasing agency who wrote the original RFP during the systems engineering phase; however, the other customer voices cannot be left out of consideration simply because they will not have responsibility for the fiscal purchase of the vehicle system. In general, it is best to develop a single set of customer requirements derived from a single identified customer. In the Kingfisher design example, both the AHS and Boeing were identified as the primary customer. Other customer voices were considered as secondary voices to the "voice of the customer" during the Kingfisher development.

There are numerous options for creating a set of customer requirements as a basis for design. The most common is a simple statement of need, which is expanded into a

listing of attributes, often combined to form a formal document-the RFP. The traditional method of synthesizing customer requirements consisted of manual reading of the RFP document, with identification of customer requirements. Once identified, the requirements are manually keyed into an MS Excel spreadsheet. This activity could take hours for simple products, or months for more complex products like aerospace vehicles. It is important to maintain a strict word by word association between the customer RFP and the extracted requirements. It would be disastrous to approximate or assume anything at this stage of development, as a misunderstanding will be physically created as a costly mistake at a later time. It is for this reason that an efficient Requirements methodology would extract the customer statements "as-is" without any modification or inferred meaning attached. This could be accomplished equally well for both simple and complex products.

For simple products, requirements authoring can be very straightforward. There may not even be a need for the customer to create an RFP. Instead, verbal instructions would be sufficient. Regardless, the engineer should create a set of customer requirements, even from casual conversations. For example, a coffee cup design may have been initiated by the simple statement "I desire to contract with you to design a new coffee cup model."

The coffee cup may have the following customer requirements defined by the engineer:

-Coffee cup shall hold not less than 6 ounces of liquid
-Coffee Cup shall be able to withstand elevated temperatures to 212 degrees F.
-Coffee Cup shall have a flat bottom
-Coffee Cup shall be cylindrical in shape
-Coffee Cup shall have a handle for grasping

These five requirements form a basic set of customer requirements for the product. Since there are a total of only five, it is not difficult to key them in manually into a digital requirements data manager, to form 5 individual requirement items. In addition, there is little need to create sub-sets of the five requirements based on engineering discipline. This is not the case for industry standard customer requirements sets that may easily contain five thousand individual customer requirements [40], as shown in Figure 4.1 and Figure 4.2. It can easily be seen that there is a need to automate the requirements handling to the greatest extent possible, in order to efficiently develop the product.

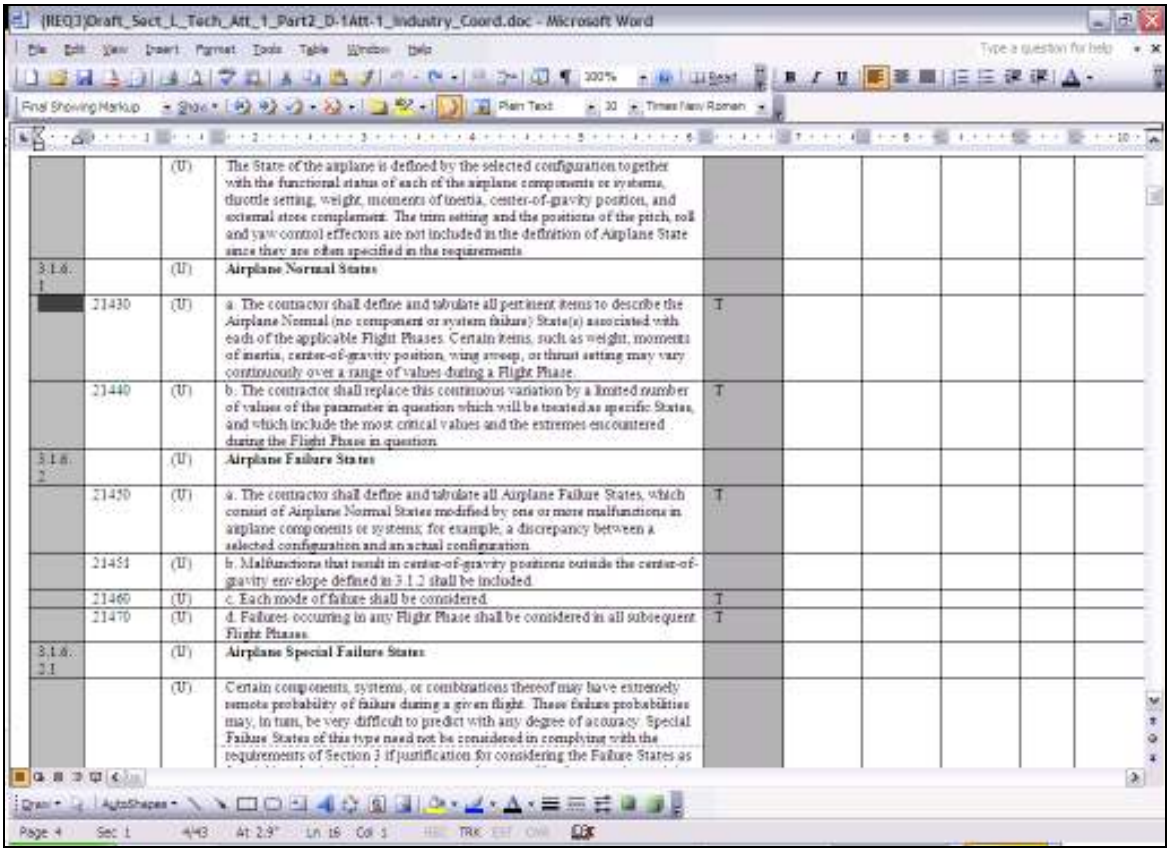


Figure 4.1 A small portion of the more than 5,711 Customer Requirements, contained in four MS Word documents. The requirements set was issued in the "BAMS-Broad Agency Announcement: Statement of Objectives (SOO)for the United States Navy Broad Area Maritime Surveillance (BAMS) Unmanned Aircraft System (UAS)-System Development & Demonstration (SDD) Phase-DRAFT, Version 4.0" Naval Air Systems Command, 2006 [18]

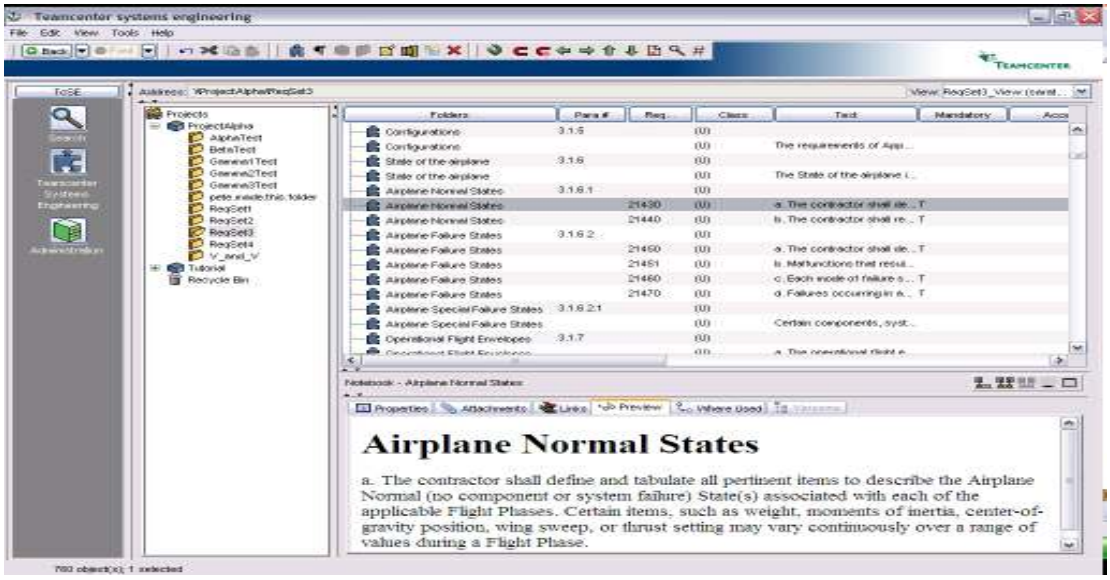


Figure 4.2: The organization of 5,711 BAMS customer requirements that were automatically Extracted, Imported, and Created in TCSE. Hart, Alston. 2007 [40]

In the case of a more complex product like an air vehicle, the customer requirement set may not be given in list format at all. It is common for a customer-generated RFP text document to act as the initial definition of customer requirements. This document often takes the form of a paper based printed document. If the customer is computer savvy, there may be the transmission of a digital format document as well, but this is not yet defined as a standard and required practice. Even as a digital text document, the RFP is in a common sentence/paragraph format, which obscures the definition of the product to the engineer somewhat. This is nearly always the case when re-encountering legacy data that was produced before widespread use of the digital computer (~1975). This was the case with the AHS RFP used in the example study. The original digital copy of the RFP was not available, even from the source (AHS). There is commonly a need to transition from the sentence format to the digital requirements

database item format with very little effort. Fortunately, a new technology is available to solve this situation.

For the example study, the paper based printed text of the RFP was digitally scanned in using a flatbed scanner to achieve a workable digital format. The RFP contained formatted text and tables, similar to Microsoft word. By scanning the document using the Optical Character Recognition (OCR) option, the printed RFP was transformed into plain text in a digital format (similar to Notepad). The entire text of the RFP was scanned in this manner. At the conclusion of the scanning, a MS Word Document was created. The MS word document allows for the manual re-formatting of the RFP words, so that the requirements data manager can more easily identify them. This final step merely eases the task of the automated extraction of the requirement items from the RFP, into the database.

This is accomplished through advanced functionality contained in the requirements data manager (Teamcenter Systems Engineering). The Import function initiates a keyword search that is performed in the body of the RFP text. The sentences containing the specified keywords are automatically copied, and created as a customer requirement item in the database. In the case of the example RFP, 15 pages of body text were scanned using the TCSE Import function. The scan resulted in an initial set of customer requirement database items. The import took approximately 10 seconds to perform after initiation, a significant savings of time and effort for this single task. Figure 4.3 displays a block diagram of the steps involved in the Requirement digitization from the RFP in the example study.

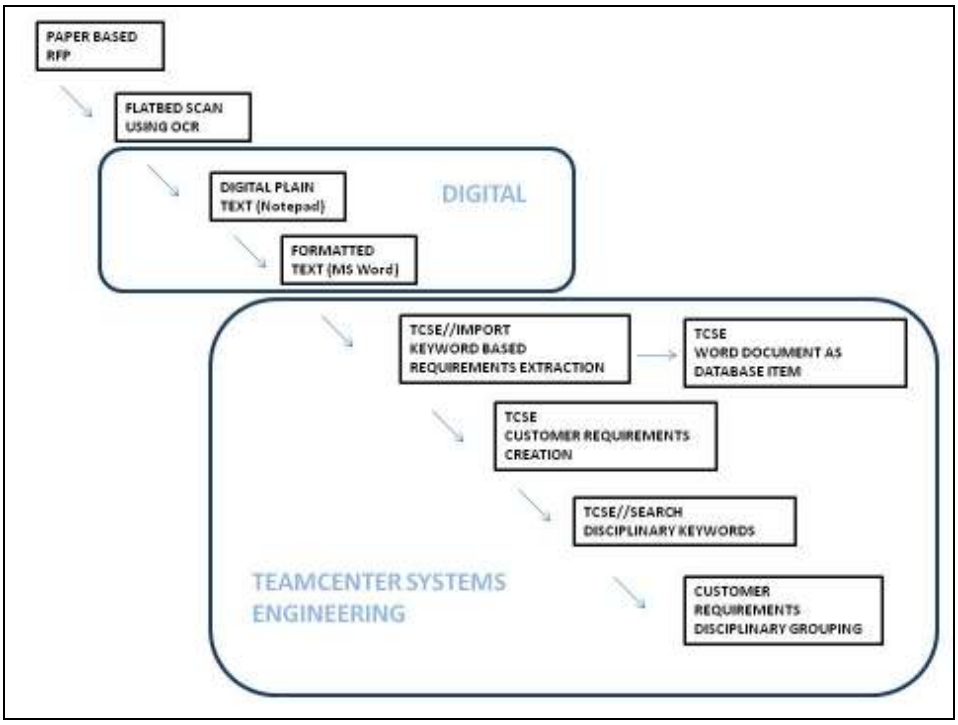


Figure 4.3: A depiction of the steps used to automate the Import of the AHS RFP into TCSE, using the flatbed scanner and TCSE requirement keyword search. Hart, 2009.

It is important to identify the keywords that are used most often in the production of the RFP. Multiple search words are possible and provided a decent extraction of customer requirements into the database. It is important to understand that some RFP authors may not use these common keywords, and so additional alternate keywords may need to be employed. A listing of the keywords used in the example search is provided in Table 4.1.

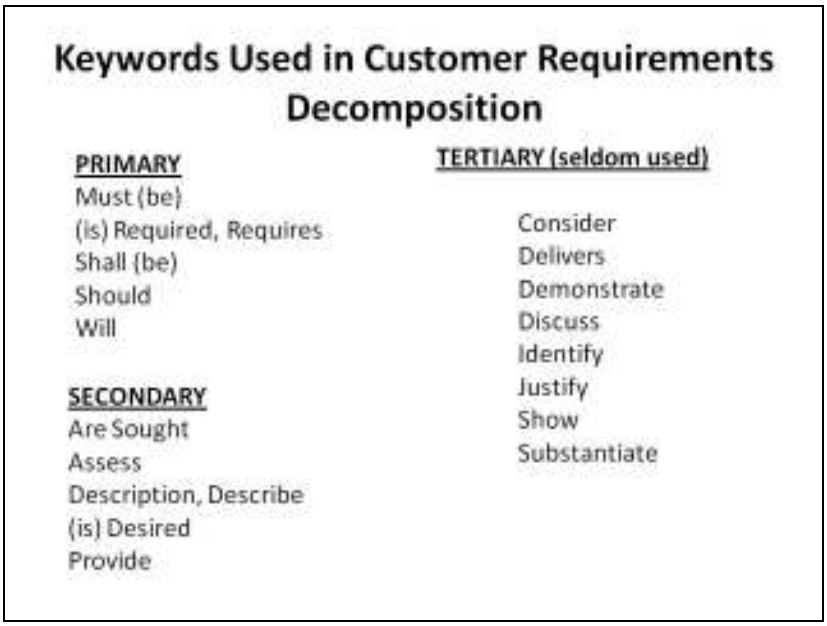


Table 4.1: A listing of the keywords used to search the 2001 AHS RFP for the purpose of the automated extraction of customer requirements, and import into TCSE. Hart, 2009.

The extraction of the customer requirement items from the RFP is the first step in digitizing the intent of the customer into a useable form. Following the creation of the customer requirement items shown in Figure 4.4, there is a need to group the requirements so that they may be manipulated more easily. This may be done according to any schema, dependent upon context. However, for aerospace vehicles whose designs are primarily multi-disciplinary, the breakdown of the requirement set by engineering domain can be extremely useful. The assignment of groups can be accomplished in two ways. The first is through the use of the Affinity Diagram, which will be discussed in future chapters. The second is through an automated keyword search on the customer requirements.

Figure 4.4: The customer requirements automatically created in TCSE after using the File//Import//MS Word functionality. Notice the automatically generated numbering scheme, compliant with the AHS RFP text section nesting. Hart, 2009.

The newly imported customer requirements in TCSE were parsed using the advanced Search function within TCSE. The search was performed by looking at keywords associated with individual engineering disciplines, as shown in Figure 4.5. For the example vehicle study, the following keywords were used:

Rotor	Mission	Structure
Propulsion	Certification	Flight Control

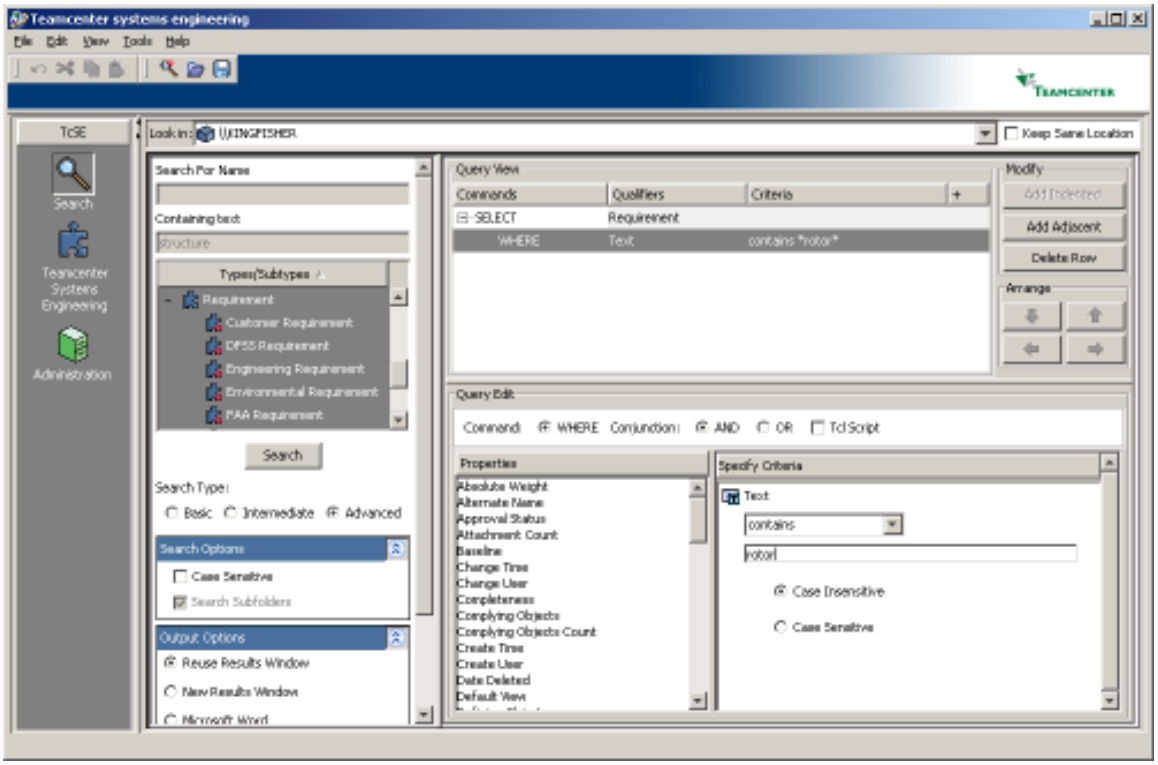


Figure 4.5: The advanced search function used to parse the newly created customer requirements according to disciplinary group. Hart, 2009

The search for keywords returned subsets of customer requirements, as shown in Figure 4.6.

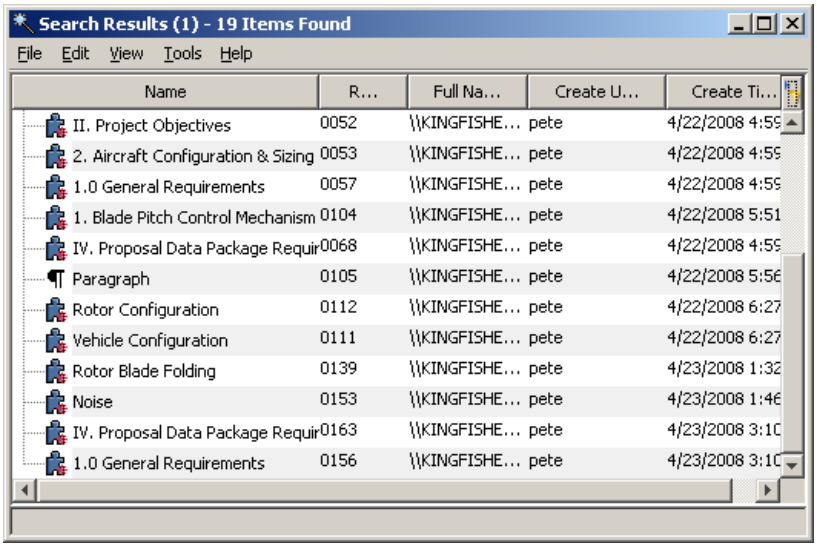


Figure 4.6: Advanced Search results in TCSE. Hart, 2009.

A derived set of requirements was created by the student team previously. These were entered manually into the TCSE database project for the Kingfisher. The derived requirements were parsed using an Affinity Diagram, and were assigned to a Group item type in TCSE. The Group item type is simply a name by which a collection of multiple data items may be referenced by a single word. The Group item type does not operate as a folder or storage device. The customer requirement item types are merely linked, logically to the Group name in TCSE. In this way, it is possible that some requirements could reside in multiple group names. The derived customer requirements and groups are shown in Figure 4.7

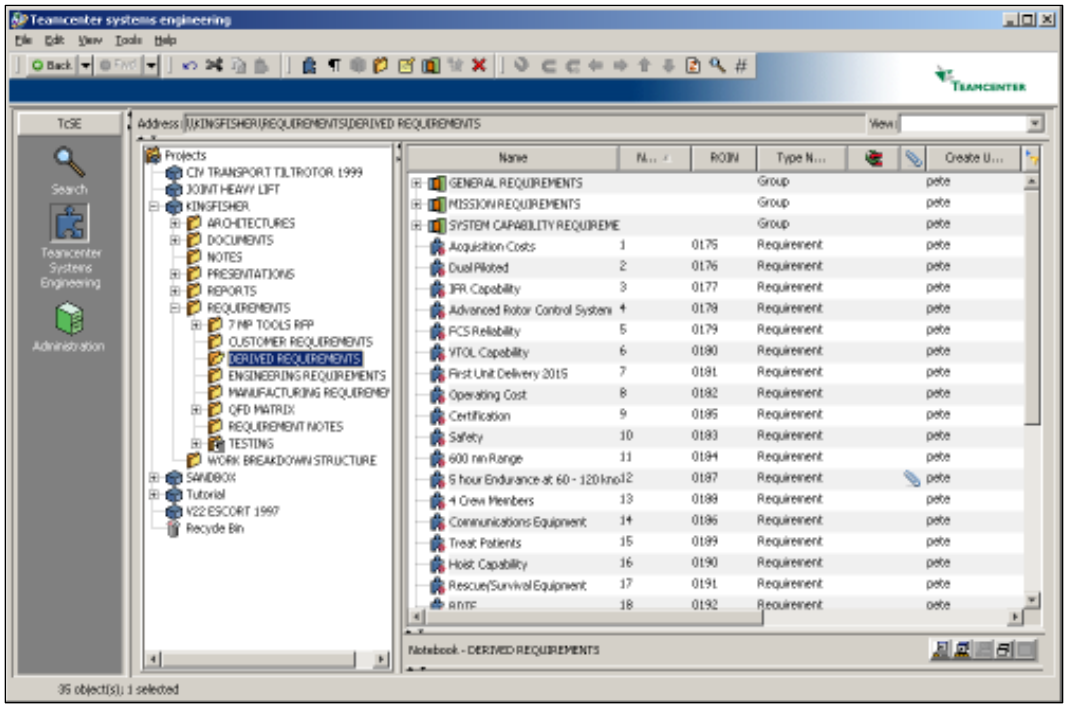


Figure 4.7: Derived customer requirements that were created by the 2001 GT Kingfisher student team. Note the depiction of the Group item types in the derived requirements folder. Hart, 2009.

Following parsing, it is beneficial to augment the customer requirement set with "metadata". This material helps to define and augment the text contained in the requirement items, without being contained in the items themselves. This type of supporting data is commonly brought into the requirement data manager as a paragraph item type, or a note item type and associated with a requirement item.

For the example study, the RFP text document itself was entered into the database, as a supporting document. There are also numerous definitions and non-requirement RFP items, which are included at various positions within the database to support the meaning of the requirements set. These could be used later as a sort of "pop-up help" during product architecture development.

CHAPTER 5

ENGINEERING REQUIREMENTS

In contrast to the customer requirements that were derived from an RFP in Chapter 4, the engineering characteristics (or requirements) are often synthesized from personal experience and domain expertise. This is accomplished through relation of direct experience, and brainstorming which is discussed below in detail. The goal is to formulate engineering characteristics that reflect and meet the challenge of the customer requirements. Given that the engineering characteristics are synthesized, there is a much greater role for past experience and legacy data sets. The capability to reduce synthesis time and effort through the re-use of data is a fundamental theme of this thesis. It is for this reason that the intelligent synthesis of engineering characteristics is seen to forms a core capture of knowledge. This can be leveraged to act as a partial project foundation for future rotorcraft designs.

While it might appear that the engineering characteristics set will be custom made to suit the customer requirement items, the fact is that, in general, a common set of engineering characteristics are applicable to nearly all flight vehicles. It is reasonable to consider these common characteristics as forming a core set of engineering characteristics, augmented with additional contextual characteristics as flight vehicle context dictates.

Rotorcraft Core Engineering Requirements
Airframe
Flight Controls
Integrated Systems
Mission Equipment
Propulsion System
Rotor and Hub System

Table 5.1: Listing of general core engineering characteristics for rotorcraft. Hart, 2009.

A core set of common engineering characteristics is listed in Table 5.1. These were derived from many years of experience in designing aerospace vehicles at the academic level. For the example case of the AHS customer requirements, the core was augmented with additional contextual characteristics based in the RFP defined mission and RFP focus on advanced flight control technologies. The engineering requirement items types are entered into TCSE manually, rather than automatically produced. The terms characteristics and requirements are used interchangeably in this thesis. However, when creating engineering characteristics in TCSE, the database item type is defined as an "Engineering Requirement." Figure 5.1 displays the engineering requirements (characteristics) for the Kingfisher vehicle design study as they were entered in TCSE.

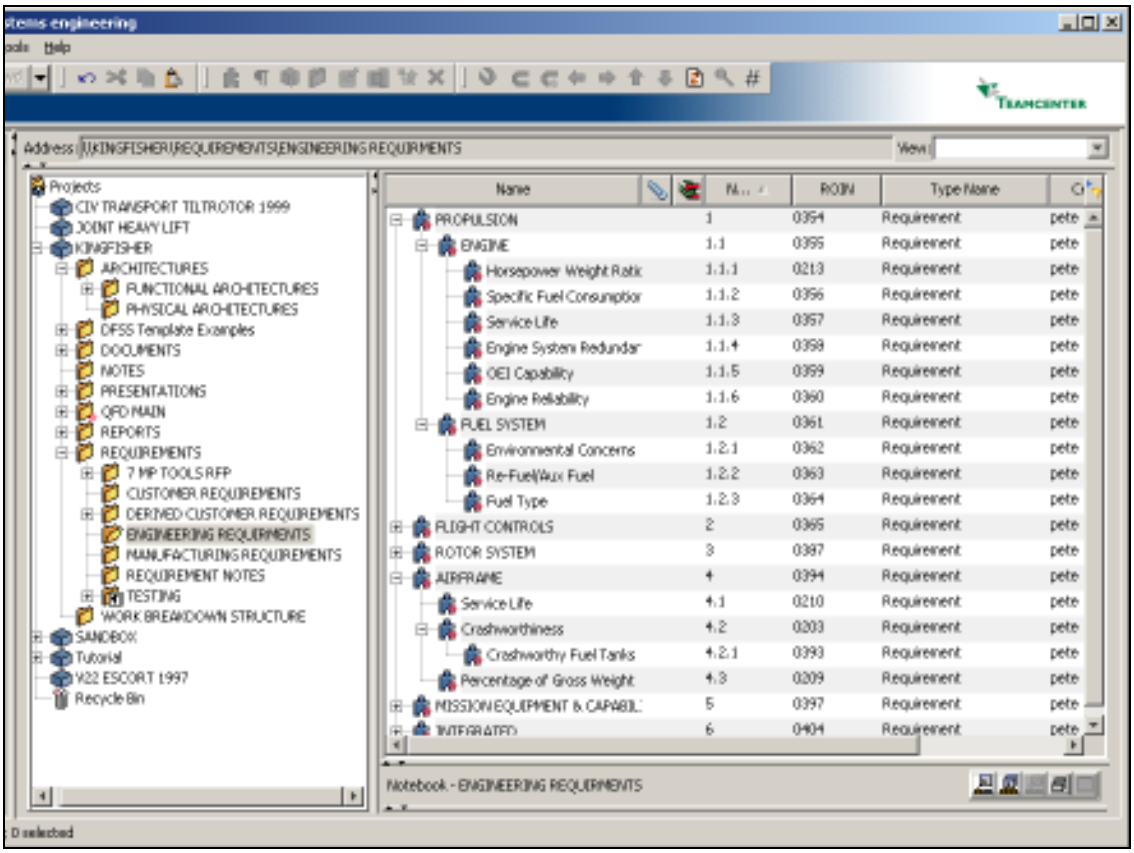


Figure 5.1: Displays the engineering requirements as entered into TCSE for the example vehicle design study. Hart, 2009.

As shown in Figure 5.1, requirement management is greatly enhanced through the use of folders, icons, and naming conventions to distinguish between the numerous requirement sets. This allows for uncomplicated navigation of the entire requirement data set with a rapid identification of data of interest for analysis purposes. The importance of organization in the requirement database items cannot be over emphasized. As the population of all requirements progresses in the IDE, there will be a need to establish "Traceability" between engineering requirements and the analyses in which they participate. Additionally, in downstream engineering design lifecycle phases, the requirements will be logically linked to the engineering product data that satisfies them. Chaos will reign during the eventual engineering lifecycle phase unless order is imposed during requirements creation.

A representative requirement data structure is imposed in Figure 5.1. However, as a basic demonstration project, the structure does not follow any best practices, that would normally be imposed by a project administrator at this point in time.

IPT in Characteristic Generation

The Integrated Product Team (IPT) is traditionally composed of subject matter experts (SME) from a variety of disciplines. This allows for a variety of backgrounds and experience to be brought to the table during engineering characteristic synthesis. The IPT need not all be engineering disciplines, as it is generally necessary to include representatives of all product lifecycle phases in the team (see Figure 3.4). In the case of the GT IPT organized to develop the AHS proposal, the members were all graduate students in aerospace engineering rotorcraft design. Fortunately, some of these were Army helicopter pilots; others were disciplinary specialists in structures, flight controls, computer-aided design, and maintenance and repair overhaul (MRO). As a team, they worked well to objectively achieve a single flight vehicle candidate that meets or exceeds all Customer expectations. However, this is not always the case.

It is common practice for the up-front engineering and manufacturing lifecycle phases to take IPT representation precedence over the other lifecycle phases. This is due to the need to rapidly develop a product that will begin to produce positive revenue. However, this tendency eventually forms a crisis due to the fact that downstream lifecycle phases have not been considered sufficiently during the Systems Engineering lifecycle phase. This becomes apparent in the MRO process design phase and more recently in the end of life (EOL) lifecycle phase. It is at this critical EOL phase that the environmental impact of system disposal is a primary importance, but considered very

late in the overall product development activity. These types of reasons mandate that the digital requirements data manager be updated and the systems engineering re-visited continuously during the product lifecycle, beyond the initial IPPD activity. There will always be a need to re-iterate on the requirements sets to perform off line analysis and situational decision making support for the Business Process Layer depicted in Figure 3.4. The proposed IDE for requirements engineering provides for an evolutionary approach to requirements definition. Through parsing and linking of the requirements, a baseline environment can be established that does not prohibit expansion and revision at some later time in the product lifecycle. IPT diversity could be a major contributing factor to the generation of a more robust engineering requirements initial dataset.

Truly useful digital systems engineering environments should facilitate participation by all of the multiple SMEs described above. In order to accurately perform the IPPD methodology, it is best practice for the team to collaborate in order to formulate and distill the design definition from multiple abstract concepts. It is insufficient for these roles to access the requirements sets solely for analysis and one time participation. In reality, there is a need for dialogue, debate, some argumentation, and often compromise on the various aspects of the vehicle system engineering. Common dialogues would include the importance assignment to requirements and ranking alternatives (through voting) and brainstorming sessions. These two activities form the basis of the IPPD methodology and should be primarily considered for functional inclusion in a next generation digital systems engineering environment.

The Teamcenter Systems Engineering database tool does not feature the functionality for collaborative brainstorming and voting internal to the tool. However,

there is a complementary tool called Teamcenter Community (TCC) [42] that is specifically functional for these activities. It is currently possible to integrate these two stand-alone tools together through data linking as shown in Figure 5.2. The Teamcenter Community tool allows for on-line collaboration, including live net meetings with application sharing and dedicated voting process functions. These capabilities play a major role in the QFD and Pugh analysis of requirements described in detail in Chapter 7. In the future (~2010), the "Teamcenter Unified Architecture" is expected to provide tighter integration between the Teamcenter Engineering, TCSE and Teamcenter Community tools.

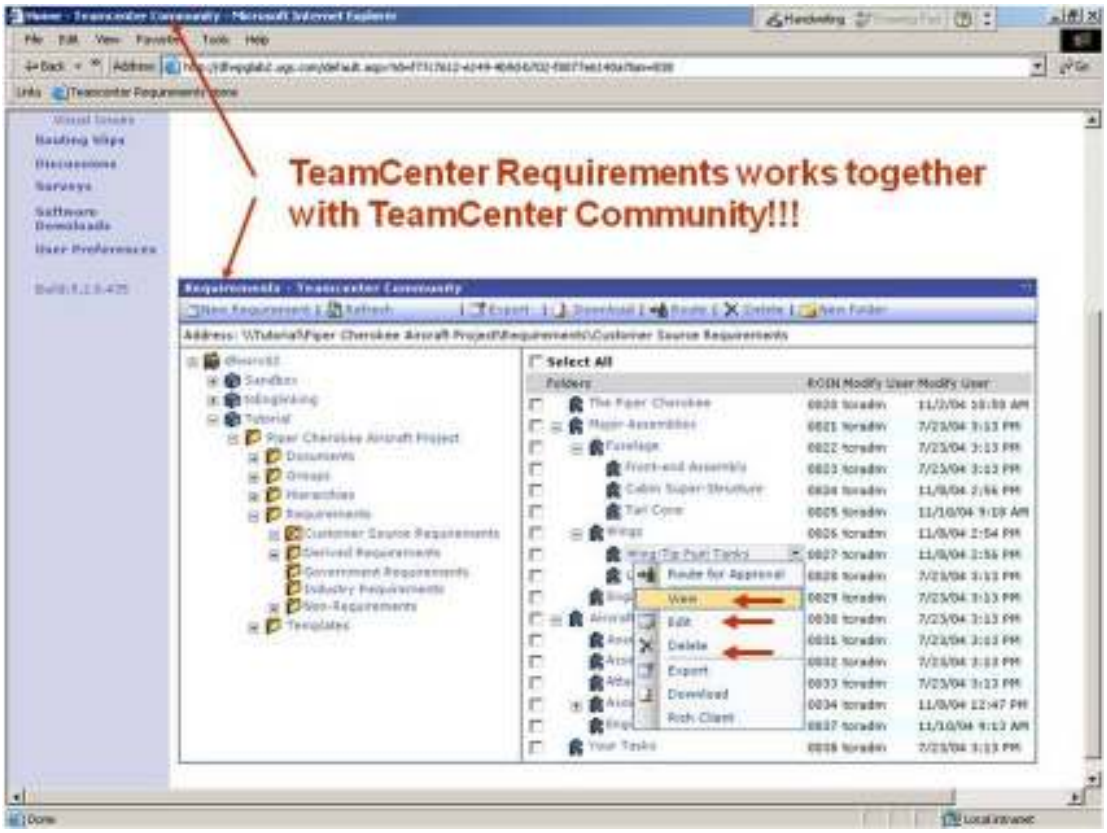


Figure 5.2: Teamcenter Community tool display featuring integration with Teamcenter Systems Engineering. Hart, 2009.

A full description of the Teamcenter Community tool functionalities is beyond the scope of this thesis. A brief review of key functions is included for the purposes of discussing the IPPD activity of engineering characteristic synthesis through the tools of Brainstorming, and Voting Surveys. The team member interface to the Kingfisher Project collaborative area in Teamcenter Community is shown in Figure 5.3.

Figure 5.3: Teamcenter Community tool showing Main Kingfisher Project site. Hart, 2009.

Teamcenter Community can be very useful as a Collaborative Environment for directly supporting the Systems Engineering team processes. The tool is primarily based on Microsoft Sharepoint Services, which uses the Microsoft SQL Database tool as a residence for shared design team-based data. TCC features a web based interface to SQL and Sharepoint Services installed on a dedicated server. TCC is accessed over the internet by installing a lightweight web client. This allows access to the data and team resources

from nearly any location, at any time, providing internet service is available. A depiction of the TCC installation infrastructure is shown in Figure 3.7.

Brainstorming

As was previously discussed, Engineering Requirements are generally synthesized based in knowledge and experience of the IPT. The act of creating these characteristics can be done in a formal collaborative IPT meeting environment. However, most engineers seem to have their best brainstorming thoughts outside of these meetings, usually at odd hours of the day or night. It is for this reason that the TCC collaborative environment could be useful in reducing the time and cost of the System Engineering phase. By providing a centralized area of collaboration among team members that is available at all hours, TCC facilitates the clear exchange of design descriptions, used to support brainstorming. The creation of this type of environment would ideally provide for the synchronous and asynchronous participation of team members. This capability is met in through functionality of the TCC tool.

When an IPT is working on a project, a whiteboard or cork board will often be used to pinup printouts of concepts, requirements and images, and to sketch out ideas. However, if design teams are geographically distributed across the globe, the cork board on the wall will not be seen. These distant teams will not be able to effectively contribute to the evolution of the design, in a timely manner. TCC is used to supply the Engineering Team with a “Digital Cork Board” for distributed team collaboration, as shown in Figure 5.4.

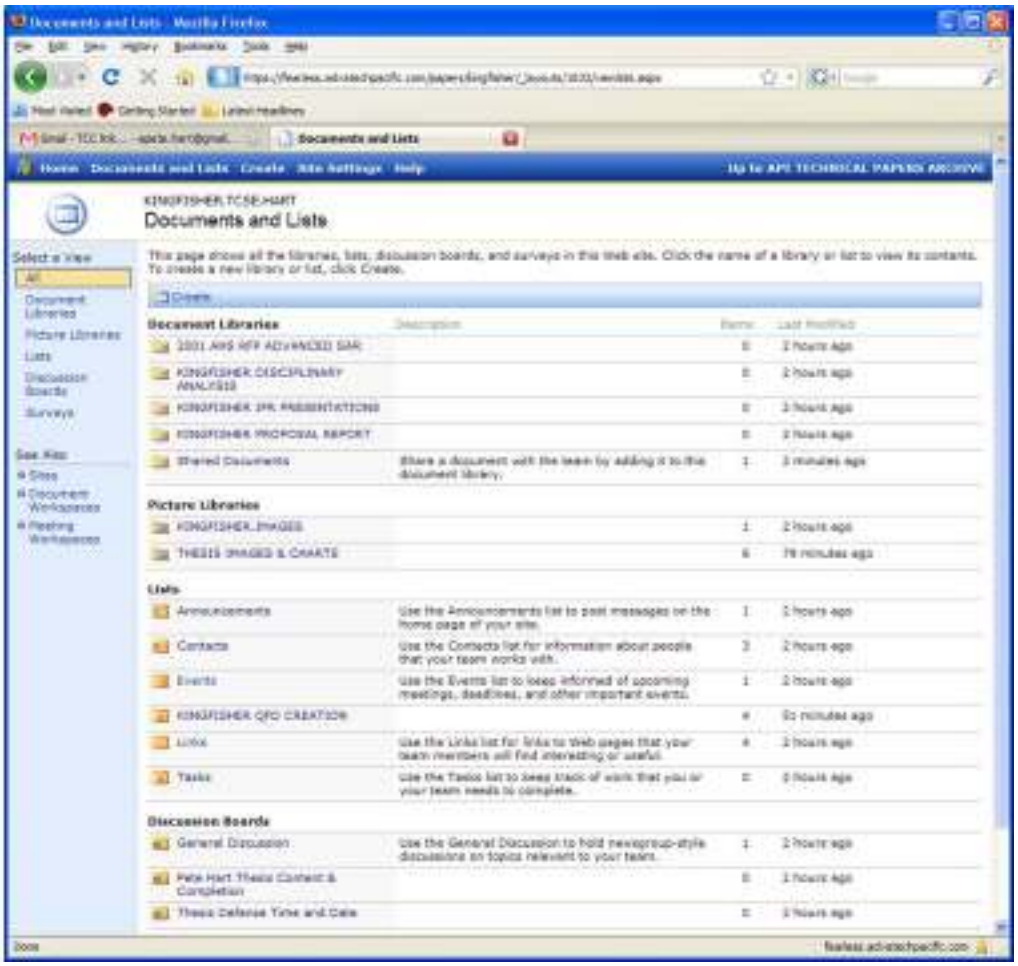


Figure 5.4: Teamcenter Community showing digital content libraries for geographically distributed IPT collaboration. Hart, 2009.

The TCC digital corkboard provides residence and access to document and image resources necessary to guide IPT activities. Additionally, the collaborative area features a discussion area, capable of capturing team member commentary and input through a "Blog" type of interface. In the modern age, this informal "texting" type of communication is rapidly replacing spoken word, and even e-mail as a new standard for conducting business communications.

The TCC "Project Workspace" is compatible with all modern forms of digital communication (as shown in Figure 5.5), including conceivably audio. Audio is not recommended for Engineering Team communications for several reasons:

-Spoken word is volatile (forgotten over time, lost in translation or volume)

-Spoken word is not keyword searchable.

-Total transcription of spoken word is difficult

-Recording spoken word is often difficult (awkward, background noise)

-Recording of spoken word is often illegal! (for teleconference meetings)

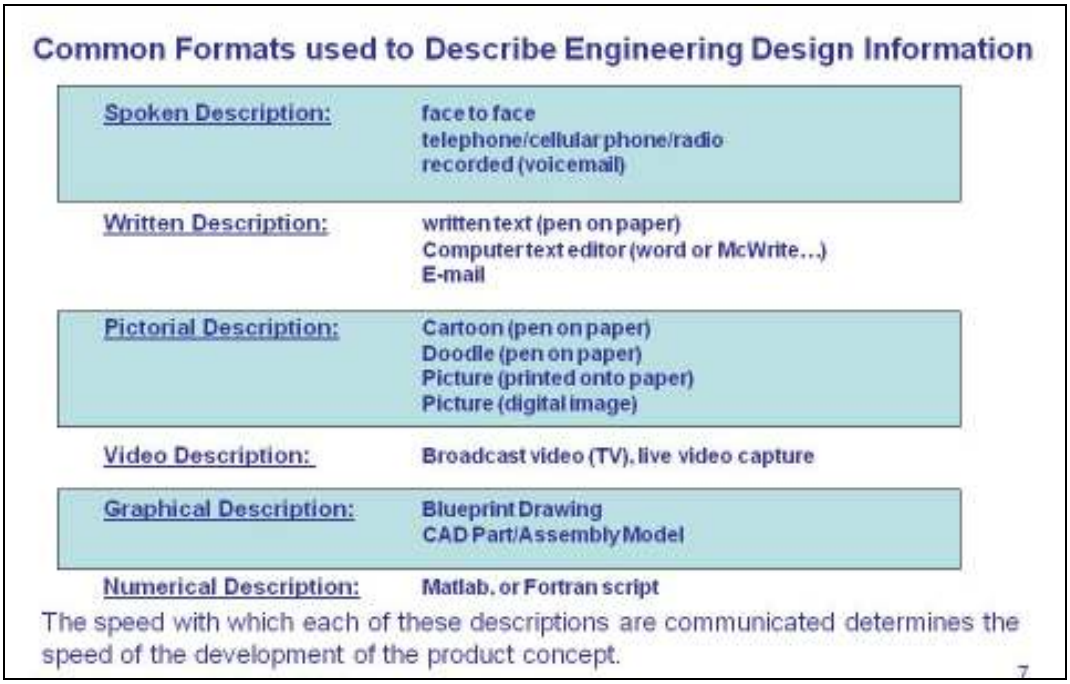


Figure 5.5: Common Digital Content Formats used to describe engineering design information and data in product team communications. Hart, 2009.

In the modern "Information Age", nearly all engineering communication is created and transmitted between IPT members in digital form. New digital formats have effectively replaced the traditional formats for engineering communications that were

previously all based in printed paper, or fiche. This has profoundly affected the modern engineer by forcing them to rely more heavily on the sharing of digital data in order to interact with other IPT members. The most common form of transmission of these formats is through electronic mail over an internet network between digital computers. E-mail has become a generally accepted, universal form of transmission for digital content, regardless of format.

Unfortunately, e-mail has several limitations. The most significant limitation of e-mail is discrete readership privileges. An entire team does not have access to read a single team member's e-mail folders. E-mail also exhibits the following limitations:

-limited global distribution to all interested parties of a team.

-distribution is not manageable and generally not verifiable

-not accessible by all individual team members

-not keyword searchable for body text

-not easily archived to protect project specific knowledge in context

-no release control of information or verification of sensitive material security

There is a need for an improved location for inter-engineering team communications so that all of the team members may have access to shared descriptions of engineering concepts. TCC could provide significant benefits to integrated product teams through solving the limitations of e-mail for the shared communication of engineering concept data.

The TCC workspace can be configured and managed by a Project Administrator so that all visits to the workspace and downloads from the site may be monitored and

logged. This maintains a strong positive motivation for team member participation. Effective team data production is managed in TCC through workflow assignment and review in a "Workflow Manager Dashboard". A typical workflow manager assignment for the Kingfisher example investigation is shown in Figure 5.6.

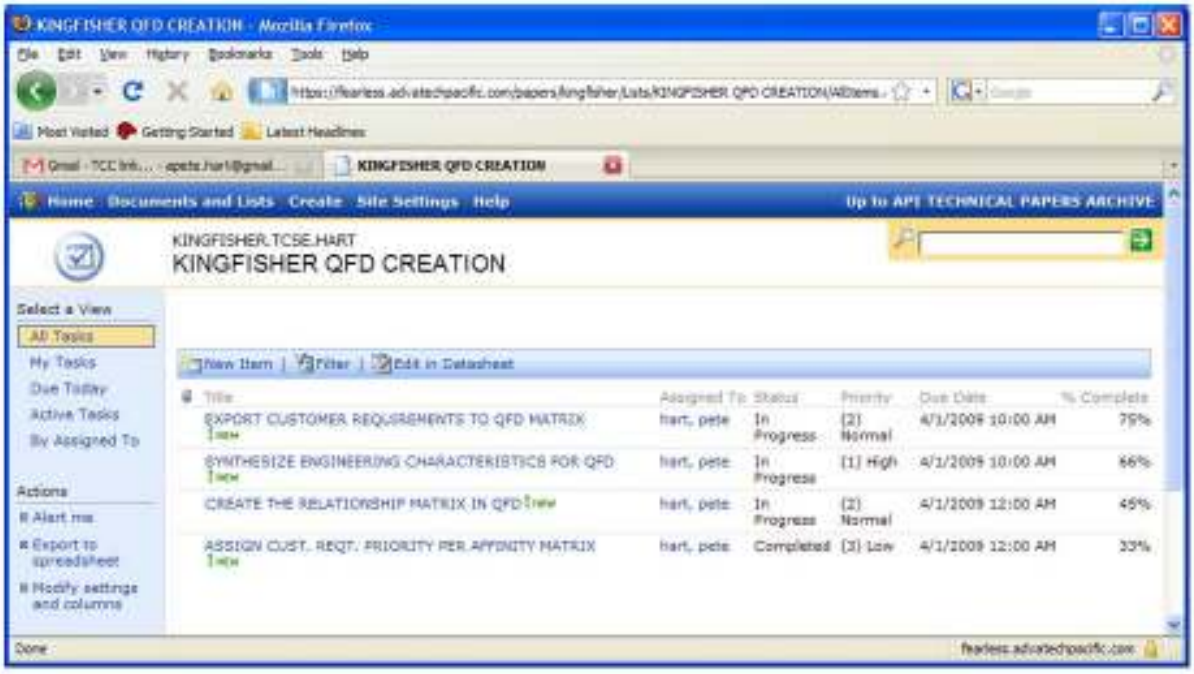


Figure 5.6: Teamcenter Community showing Project Team Manager View of Workflow Manager. Task assignment and status of work completion can be seen in this dashboard view. Hart, 2009.

The Team can also be automatically notified about changes to a specific project workspace through individual subscription to "Alerts". There are several levels of TCC workspace activity that may be set to trigger an automatically generated e-mail alert broadcast such as an addition, change, or update. It is conceivable that e-mail alerts could also be sent as "text" to a wireless device. The TCC alert configuration tool is depicted in Figure 5.7. Alert notifications can be restricted to daily, weekly, or other settings. This

protects team members from getting flooded by e-mail alerts about changes to the TCC workspace(s).

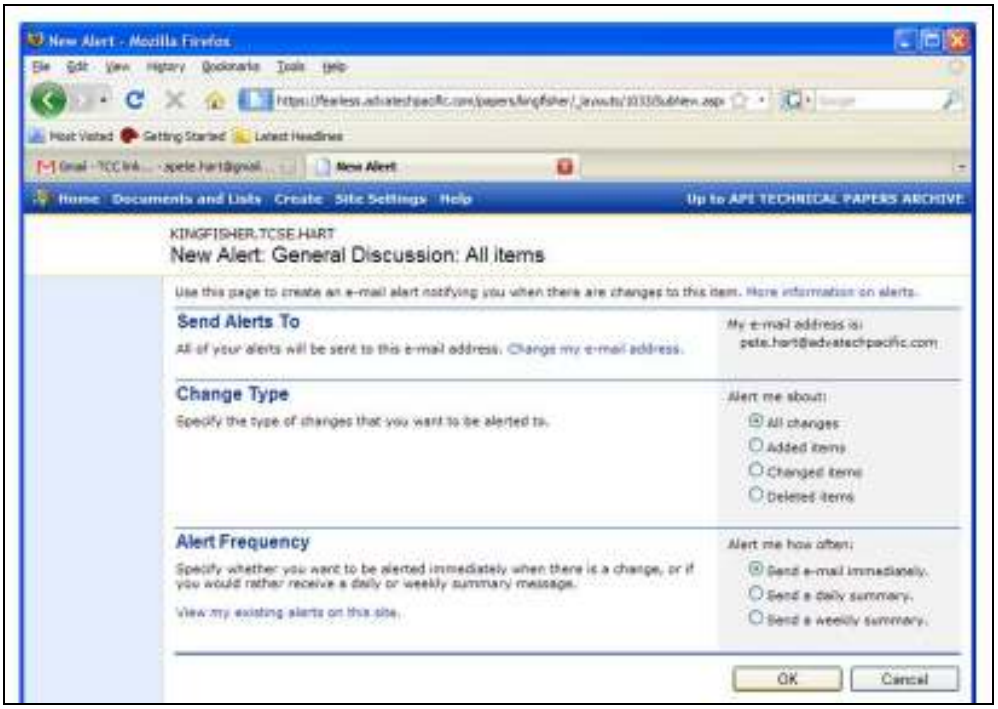


Figure 5.7: Teamcenter Community showing the ability to create automatic notifications by "triggers" established by the management role. Triggers can consist of simple TCC area access by team members, updates to data, and posting of new data. [42]

Survey

The IPPD methodology features a strong reliance on importance assignment and ranking. These are subjective activities are traditionally performed in team meetings where all of the members are co-located to agree on value assignments. Given the reality of globally distributed team members, there is a need to accommodate this type of "voting" or "survey" activity so that the entire IPT can contribute. This is accomplished in the TCC tool through a functionality for producing "Surveys".

Before a survey or poll may be taken, it must first be created. The survey creation function in TCC is shown in Figure 5.8. A wide variety of survey options are available,

including provision for free text response to individual survey questions. The Kingfisher example is featured in the survey shown in Figure 5.8. It represents a typical team survey question that was used during the Kingfisher systems engineering development. Basically, there is a query of the team as to which technology they feel is most appropriate for the overall vehicle system hull/propulsion configuration. A second question addresses the selection of a single technology for advanced rotor control. As related elsewhere in the thesis, this survey played a pivotal role in the development of the Kingfisher vehicle system.

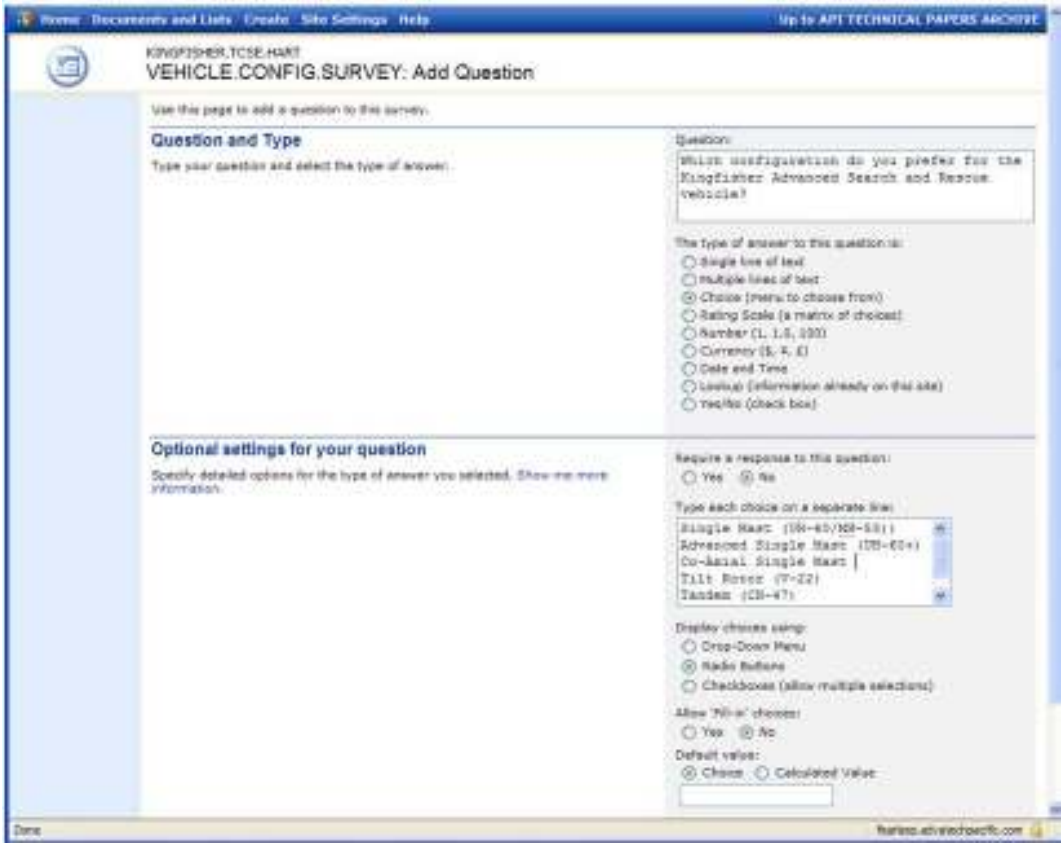


Figure 5.8: Teamcenter Community showing the creation of a Team Survey. [42]

Once the survey is created, a notification is sent to the team through either a workflow assignment e-mail, or automated alert, instructing them that the survey is

available, and awaiting their response. When the team member accesses the survey, it could appear similar to Figure 5.9. This is a depiction of the survey generated as an example for the Kingfisher configuration and advanced rotor control.

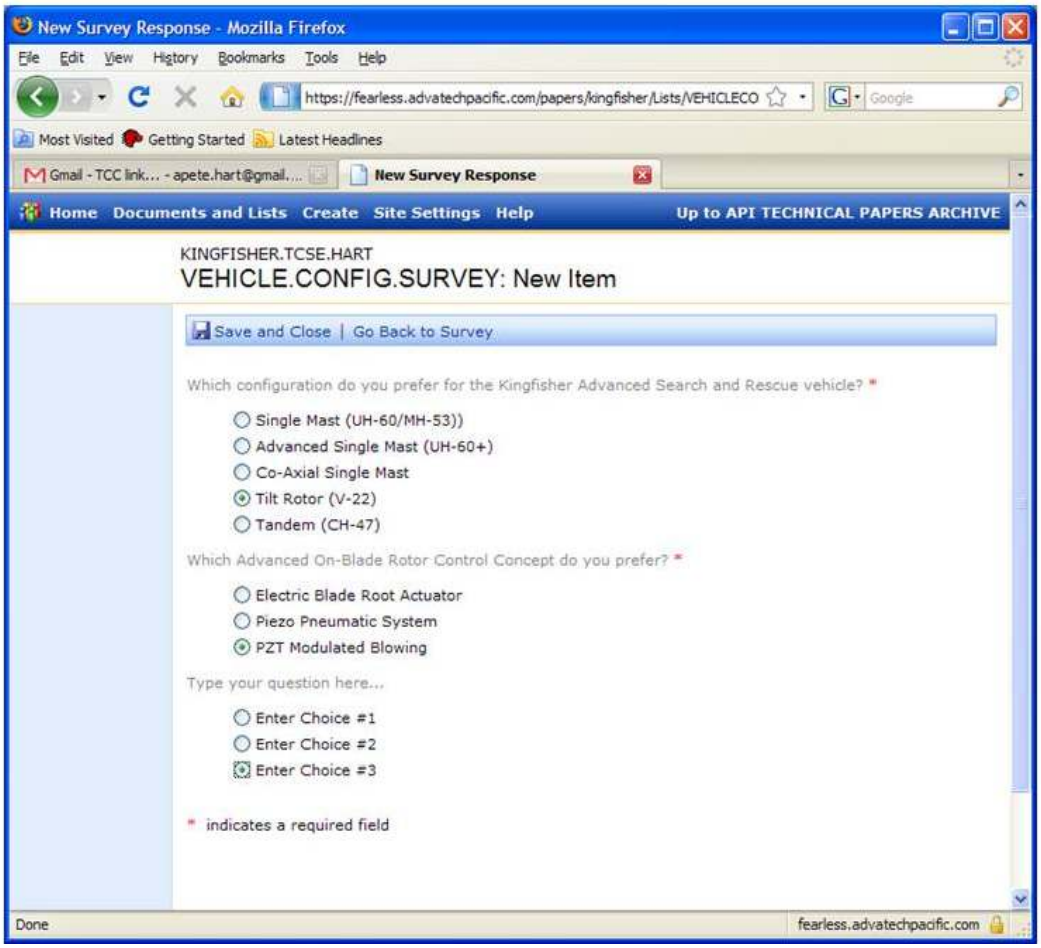


Figure 5.9: Teamcenter Community showing the conduction of a Team Survey.

Once the survey is completed by the team members, the results can be tabulated in a dedicated survey "dashboard". This is shown in Figure 5.6. This TCC function provides a record of the team survey activity. The engineering project team manager could attach the results of the TCC survey to the appropriate folder in the TCSE tool through the use of the "Export results to a spreadsheet" function shown in Figure 5.10.

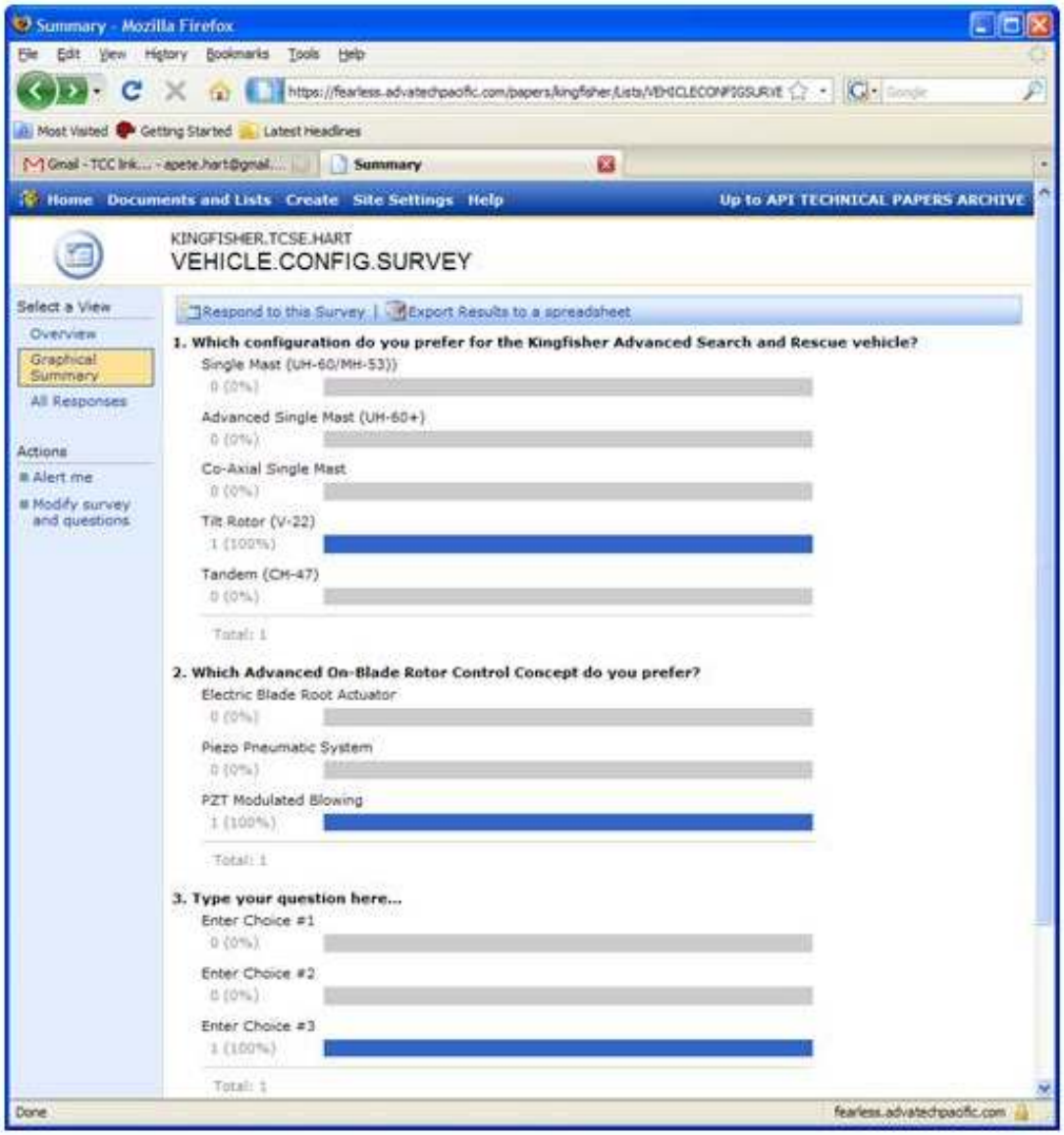


Figure 5.10: Teamcenter Community showing the management view results of a Team Survey. Effectively creating a decision "dashboard" that can be used to document voting surveys, and their results in a formal manner. [42]

Teamcenter Community can be thought of as the "Product Team Communications Manager". As such, TCC could provide an accessible and integrated collaborative environment dedicated to the synthesis of engineering characteristics through brainstorming. It is proposed that a best practice could be established whereby actual systems engineering data sets and tools would reside within TCSE, but evolve through

brainstorming, discussions, and surveys hosted and captured within the integrated TCC tool.

CHAPTER 6

QUALITATIVE ANALYSIS

The use of graphical tools to organize data sets and expose trends has been common practice for several decades. Through the adaptation and use of these tools over the years, a few have been identified to provide specific value towards the process of Systems Engineering of Air vehicles. These are described below as the "Seven Management and Planning Tools" (7 MaP tools) [39]. The engineer is certainly not limited to the use of only these tools. As well, the engineer should not feel any pressure to use all seven in any given IPPD activity. The general utility of these tools in streamlining the design process is what we are after here, not the specific number of total tools used.

The 7 MaP tools are used to visually accumulate both the customer requirements and the engineering requirements so that they may be evaluated and ranked. Often, it is not possible to evaluate and rank all of the imported customer requirements (and their associated engineering requirements). Instead, the visual array of the requirement items is examined for "the most important contributing factors." This is often taken to limit the number of requirement items under consideration in the 7 MaP tools to about 10-15 items. This is typical for a manual IPPD process in conceptual design at the academic level, similar to the example vehicle. In more realistic industry situations involving a similar vehicle, the customer requirement items may number in the thousands. This situation makes the baseline selection of "most important contributing factors" for practical first cut analysis all the more important to reduce time and costs. An increase in

the number of items considered could be a natural outcome of using a digital environment, rather than a traditional process involving sticky note papers. However, this point was not explored in the current work.

Several of the 7 MaP tools described in this thesis will be:

1. Affinity Diagram
2. Tree Diagram
3. Inter Relationship Diagram
4. Morphological Matrix
5. Brainstorming (discussed in Chapter 5)
6. Prioritization Matrix
    - Pugh Evaluation Matrix (discussed in Chapter 7.)
    - Morphological Matrix of Alternatives (discussed in Chapter 7.)

Table 6.1: Several of the 7 Management and Planning (7 MaP) tools used in the IPPD Methodology. [16], [39]

Affinity Diagram

The Affinity Diagram is used to group data according to some agreed upon criteria or natural similarity between items, so that the data can be more efficiently considered by the IPT. In the case of the Kingfisher, the Affinity Diagram was used to group similar requirements together. Once the grouping was accomplished for like requirements, a group name was attached to each of the groupings so that they might be more readily identified and handled for subsequent analysis.

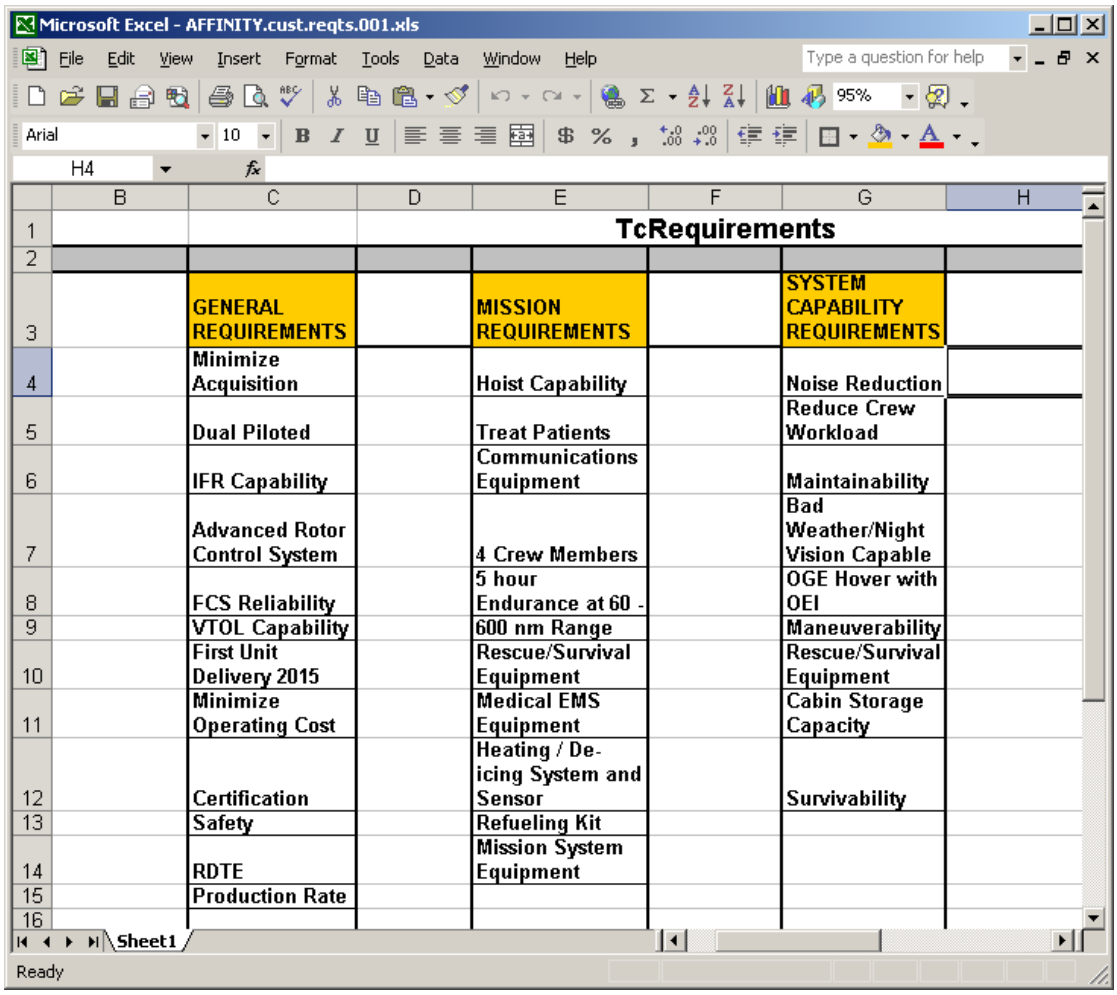
The Affinity Diagram was used twice in the Kingfisher project. Once to work with the customer requirements, and once with the engineering requirements. The affinity

diagram allowed the team to consider groupings of the requirements, aside from the engineering disciplinary parsing to prepare the requirements for insertion into the QFD matrix. This was important due to the fact that there were numerous mission and performance-based requirements that were routine, in addition to several contextual requirements specific to the RFP. It was necessary to insure that the contextual requirements (for the new, non-swash plate flight control system) did not get demoted in importance to the routine vehicle design consideration.

The Affinity Diagram can be populated automatically from the requirement data manager item sets for both the customer and engineering requirements. This is done as an EXPORT of the requirement items into a MS Excel spreadsheet from (TCSE). There is no need to export as an Excel LIVE workbook, due to the fact that the Affinity Diagram is only a visual aid, and not a computational analysis tool. The use of Excel makes it easy to drag and drop the exported requirements into groupings by either column or row. The registration of the Excel file containing the Affinity Diagram into the Requirements Data Manager provides a secured location for the data within the TCSE project. The diagram will remain intimately located with all of the requirement datasets. All IPT members can look up the diagram at any time. Also, it can be versioned and then modified to reflect additions or subtractions of requirement items in the database as the design matures through the lifecycle phases.

Once the groupings are established, headings can be assigned to each of the groups. The requirements are arranged according to a criteria established by the team for the vehicle design. It is important to note that in some cases, a requirement may need to have duplication in two or more of the groupings. This is permissible for the affinity

diagram, but was not necessary in the Kingfisher work. In the case of the Kingfisher, the requirements were grouped as shown in Figures 6.1 and 6.2.



Microsoft Excel - AFFINITY.cust.reqts.001.xls

File Edit View Insert Format Tools Data Window Help

Type a question for help

Arial 10

H4

	B	C	D	E	F	G	H
1		TcRequirements					
2							
3		GENERAL REQUIREMENTS		MISSION REQUIREMENTS		SYSTEM CAPABILITY REQUIREMENTS	
4		Minimize Acquisition		Hoist Capability		Noise Reduction	
5		Dual Piloted		Treat Patients		Reduce Crew Workload	
6		IFR Capability		Communications Equipment		Maintainability	
7		Advanced Rotor Control System		4 Crew Members		Bad Weather/Night Vision Capable	
8		FCS Reliability		5 hour Endurance at 60 -		OGE Hover with OEI	
9		VTOL Capability		600 nm Range		Maneuverability	
10		First Unit Delivery 2015		Rescue/Survival Equipment		Rescue/Survival Equipment	
11		Minimize Operating Cost		Medical EMS Equipment		Cabin Storage Capacity	
12		Certification		Heating / De-icing System and Sensor		Survivability	
13		Safety		Refueling Kit			
14		RDTE		Mission System Equipment			
15		Production Rate					
16							

Sheet1

Ready

Figure 6.1: Kingfisher Affinity Diagram for Derived Customer Requirements. Hart, 2009.

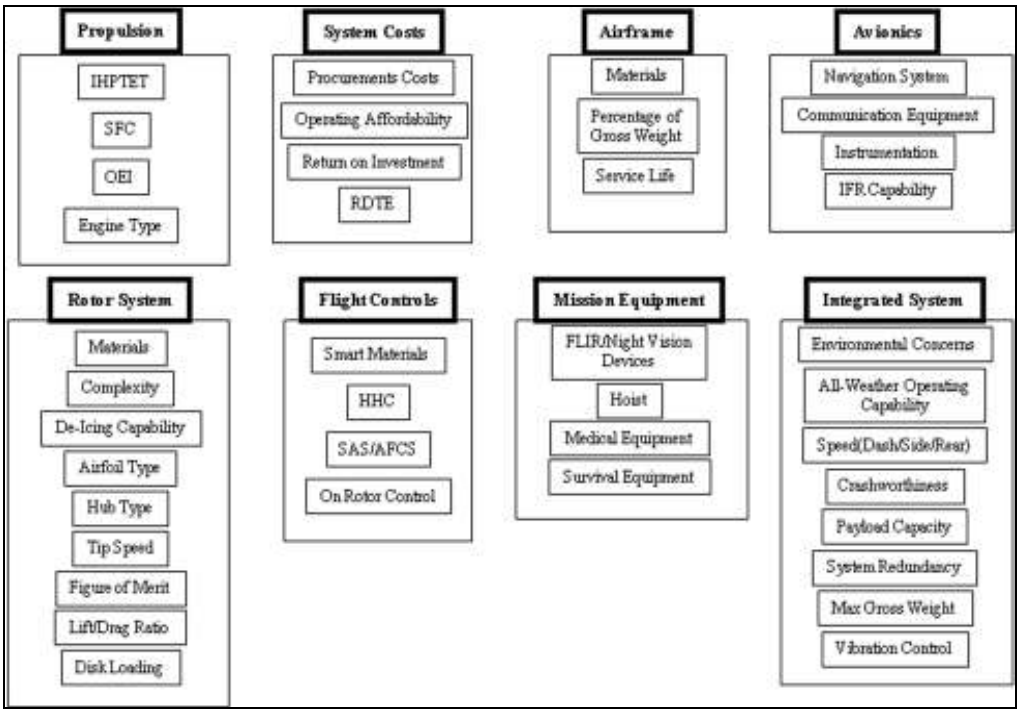


Figure 6.2: Kingfisher Affinity Diagram for Engineering Requirements. [43]

The establishment of Group headings in the Affinity diagram becomes useful outside of the tool as well. The group names can be assigned to the Group item type within TCSE to record the associations that were identified in the affinity diagram. This is a convenient way to deal with large sets of requirement items by operating on the less numerous grouping names rather than the multitude of individual requirement items.

Note that a Group does not act as a container for the requirements. Rather it is simply a name given to associate multiple requirements that have some given similarity. It is possible for a single requirement to reside in multiple Groups. This is permissible, as long as the context of the Group permits according to rules established by the TCSE project administrator. The Group does not contain the requirements. The requirements are associated with the group through logical links established in the database. A query can

be performed to determine which Groups contain a given requirement enrollment. This query is available as the “Where Used” function in the Properties window of TCSE in the lower right corner. This is an extremely useful function in the performance of impact assessments for surgical changes made to the database items.

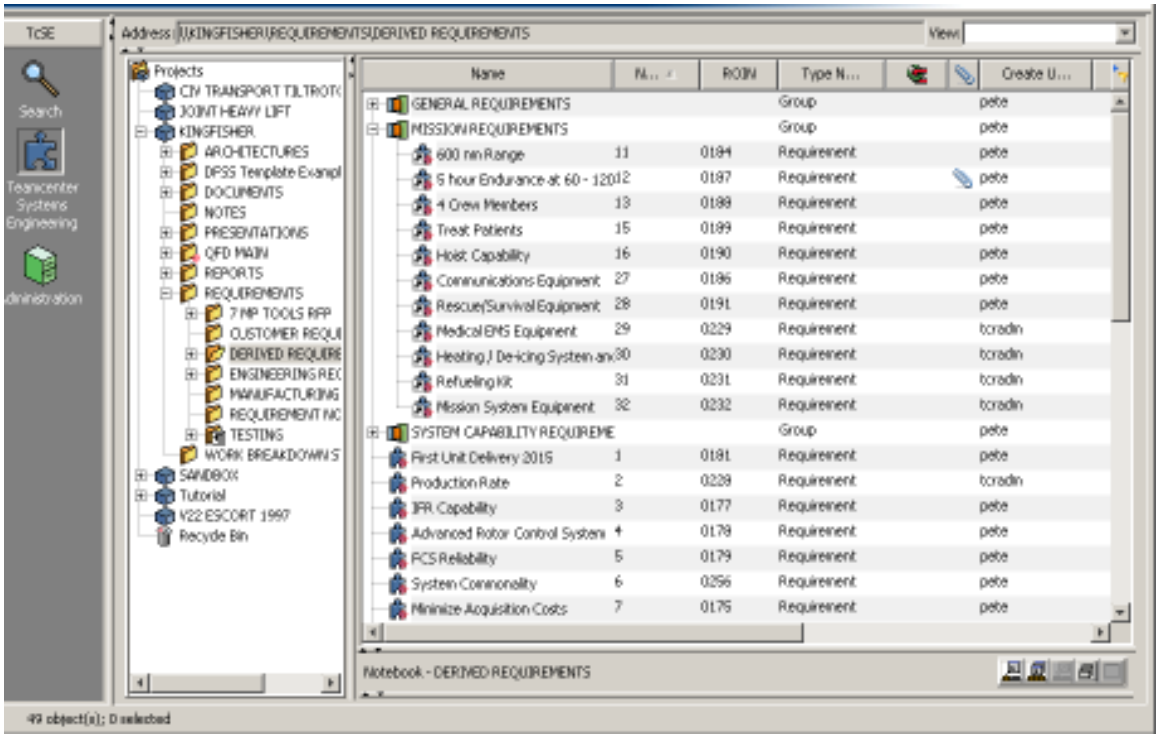


Figure 6.3: Group Item Type Requirement Assignment in TCSE. Hart, 2009.

Tree Diagram

A Tree Diagram is used to provide a logical, hierarchical structure to data sets. It is similar in creation to the Affinity Diagram, except that the data (requirements) arrangements are augmented with parent/child relationships. The depth of hierarchy is not limited in the tree diagram. However, as a preliminary data visualization tool, it is appropriate to generally limit the levels to two. In addition, it is also useful to re-use the

group names that were established in the affinity diagram to act as parent nodes in the Tree diagram.

The Tree Diagram was also used twice in the Kingfisher design example. Once to work with the customer requirements and once with the engineering requirements. Again, the data was automatically created in the MS Excel spreadsheet through the Export command in the Requirements Data Manager. This reduced the amount of time needed to create the Diagram. As a digital file, it can also provide a template for future use on a similar rotorcraft vehicle development. Interred as a document item in the database, the diagram forms a component of the requirements data set. The knowledge that is captured in the diagram is retained in a readily useable format, directly available for copy/paste into future requirements development projects.

The digitization of the Affinity Diagram and the Tree Diagram may appear to be the simply logical application of common computer technology. However, the recovery and re-use of the datasets and their associated diagrams is an important feature that is not available through the traditional methods of large poster papers covered in sticky note papers. The new reality of remotely located members of an IPT participating in the construction of digital diagrams in real time is another significant contribution to the reduction of time and cost associated with these activities.

It is important to note that the Affinity Diagrams and the Tree Diagrams (like many of the other 7 MaP tools) can be populated automatically from a single set of requirement items in the database. This reduces the chance for human error in the selection of inappropriate requirement items and the chance that some requirements

might be left out of consideration. This is one of the unseen benefits from digitization of the formerly manual processes associated with the 7 MaP tools.

There is no need to export the data into the Tree Diagram as an Excel LIVE workbook, due to the fact that the Tree Diagram is only a visual aid and not a computational analysis tool. The use of Excel makes it easy to drag and drop the exported requirements into hierarchical listings by column. Indented cells maintain the hierarchy in the Excel spreadsheet. The Tree diagram used in the Kingfisher example is shown in Figure 6.3, and Figure 6.4. This same functionality could be achieved through the use of MS Word or MS Visio, with no loss of fidelity. The Tree diagram is a visual tool, and it is of little consequence which office productivity software is used to accomplish the visualization. This is not true for the Inter relationship diagram, as we will see in the following section.

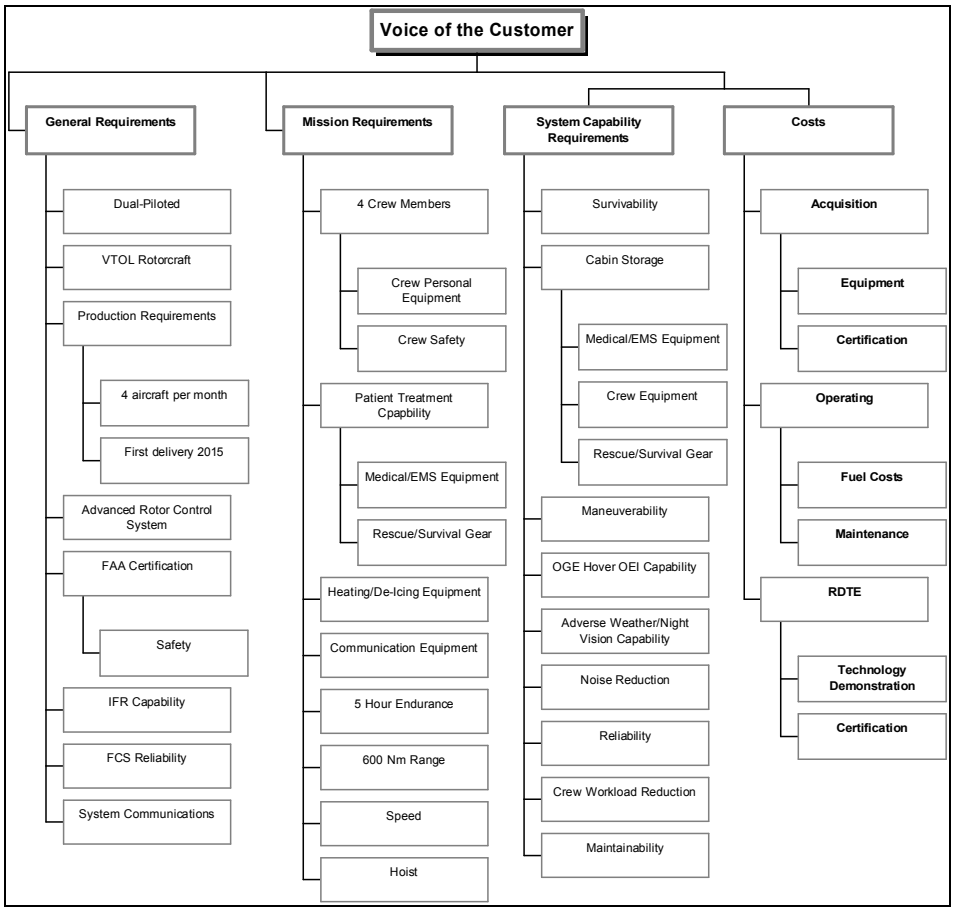


Figure 6.4: Kingfisher Tree Diagram for Customer Requirements.[43]

Inter-Relationship Diagram

An inter-relationship diagram is a graphical analysis tool used to determine precedence among competing datasets (requirement items). The process uses a system of nodes identified as the requirements. The nodes are arranged around the periphery of a circular pattern. Each node is then evaluated in relationship to each of the other nodes. The evaluation is two parts, considering first if there is a relationship between the two nodes, and second which is the cause/effect among the two. If there is a relationship between the nodes, an arrow is drawn from the identified cause node to the effected node. This process is repeated as a permutation among all of the nodes in sequence.

At the conclusion of the evaluation and arrow assignment, a count is made on each node as to the number of arrows entering and leaving. These are added up and recorded for each node. The value of the Inter-relationship diagram is in the clear identification of the causes by the highest total number of arrows originating from a node. Effects are also identified according to the highest total number of arrows entering a node. The utility of the inter-relationship diagram is to identify for the team which requirements take precedence over others. Addressing causes early-on will drive the outcome of the effects. In this manner, the inter relationship diagram takes on a computational nature, through the summing of the arrow heads and tails. (It is not recommended to make double headed arrows when using this particular 7MaP tool.) [39]

Traditionally, the inter relationship diagram is created on a large piece of paper, with sticky sheets of paper acting as the nodes arranged around the perimeter of the page. Lines and arrows are drawn between the related nodes, and the center of the circular area becomes like a bowl of spaghetti. If, during storage of this large paper, a sticky note should dislodge or fall off completely, then the value of the diagram is completely compromised. This problem has recently been addressed by re-creation of the diagram using a presentation program similar to MS PowerPoint. Unfortunately, this version of the diagram was only useful as an image of the large paper, with no intelligence or analysis capability. As a static image of the inter relationship diagram, this representation has little to no value as a functional tool over the course of the product lifecycle. In fact, the creation of a diagram image in this manner was confusing, as the image was not versioned, and not under configuration control. In other words, the image could be from

the first draft of an inter relationship diagram, or an intermediate edition, neither of which reflected the final edition.

The inter-relationship diagram may also be enrolled within the digital environment of the Requirement data manager (TCSE), where it is automatically versioned. However, the MS Excel spreadsheet tool is not appropriate for creating this diagram. It is better to use the MS Visio tool to create the inter relationship diagram.

Diagrams, such as Tree diagrams and Inter relationship diagrams can be created using the Microsoft VISIO tool. The TCSE/Visio interface is used to create diagrams based on the children of a chosen parent object in the database through the export function. Diagrams can be attached to TCSE folder items, requirement data items, building block items, and group assignments. During the creation of the Visio live stencil, the properties of the TCSE data items are mapped onto the text properties of the Visio shapes.

The Visio stencils are used to provide a richer visualization of the data sets through the addition of connections between objects, color, as well as non TCSE objects (notes, images…). These graphical enhancements can provide increased understanding in a rapid manner as compared to viewing the datasets as a listing in the TCSE interface. The graphical enhancements provide more than visual appeal. The Visio connection objects can be viewed in the TCSE “Relations” sub-tab of the Links tab. These connections are used to represent a relationship, or existence of an interface between the items, that has an associated characteristic. In addition, database objects portrayed in the Visio diagram are shown in the “Where Used” tab of the notebook window pane (lower right window).

Using the MS Visio tool, the requirements dataset can be exported, and diagrammed as a Visio stencil. This is a template that is created establishing the selected dataset items simply as nodes. Once the nodes are arranged manually in the tool, the IPT can begin the process of evaluating relationships and assigning the cause/effect arrows. (A template could be made with the nodes pre-positioned in a circular periphery as needed. Export would simply populate the nodes in the template with the appropriate requirement item ID.) The inter relationship diagram for the example Kingfisher vehicle is shown in Figure 6.5 and Figure 6.6.

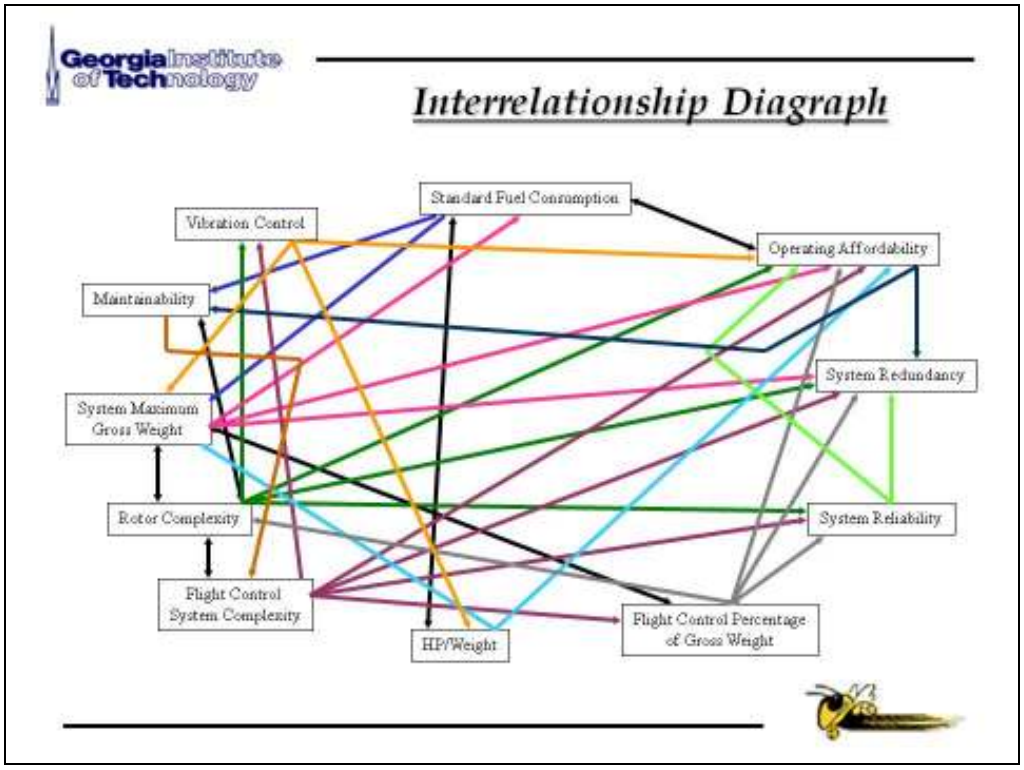


Figure 6.5: Kingfisher Inter-Relationship Diagram from the Original 2000 IPPD effort on the AHS RFP. Georgia Tech Aerospace Engineering Graduate AHS Design Competition Team, 2000. [43]

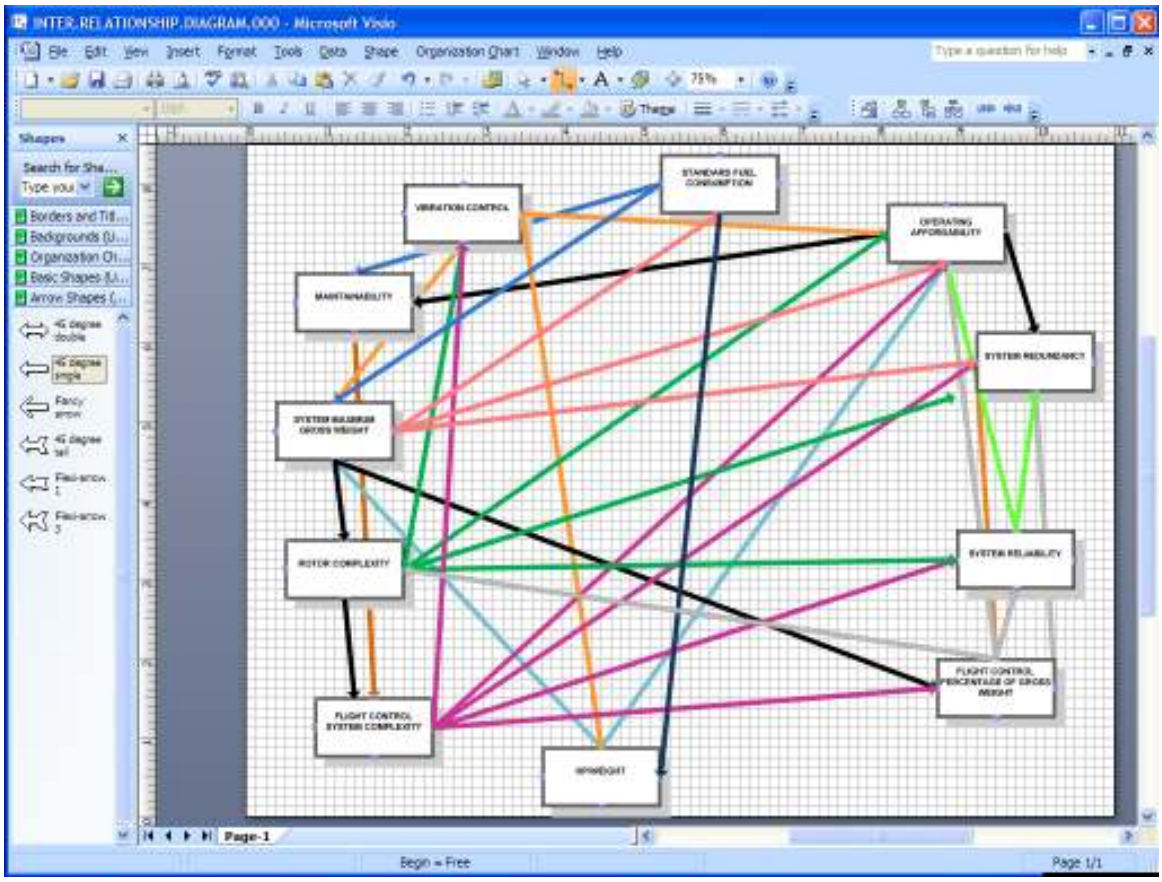


Figure 6.6. Kingfisher Inter Relationship Diagram image from TCSE/Visio integration. Hart, 2009.

Morphological Matrix of Alternatives

A morphological matrix of alternatives is used to establish a set of functional characteristic alternatives that will later be re-grouped and evaluated to establish a spectrum of functional architectures. Simple in construction, the morph matrix is used to display the characteristic candidates, arranged by grouping or discipline, that satisfy the engineering requirements. The arrangement is traditionally accomplished for aerospace vehicles by listing the technologies associated with both existing and notional vehicle systems. There is an opportunity here to include technologies in the morph matrix that have lower TRL. In this manner, the morphological matrix forms a single view of the

competing characteristics (technologies) options that are available for consideration, in the given context of the design.

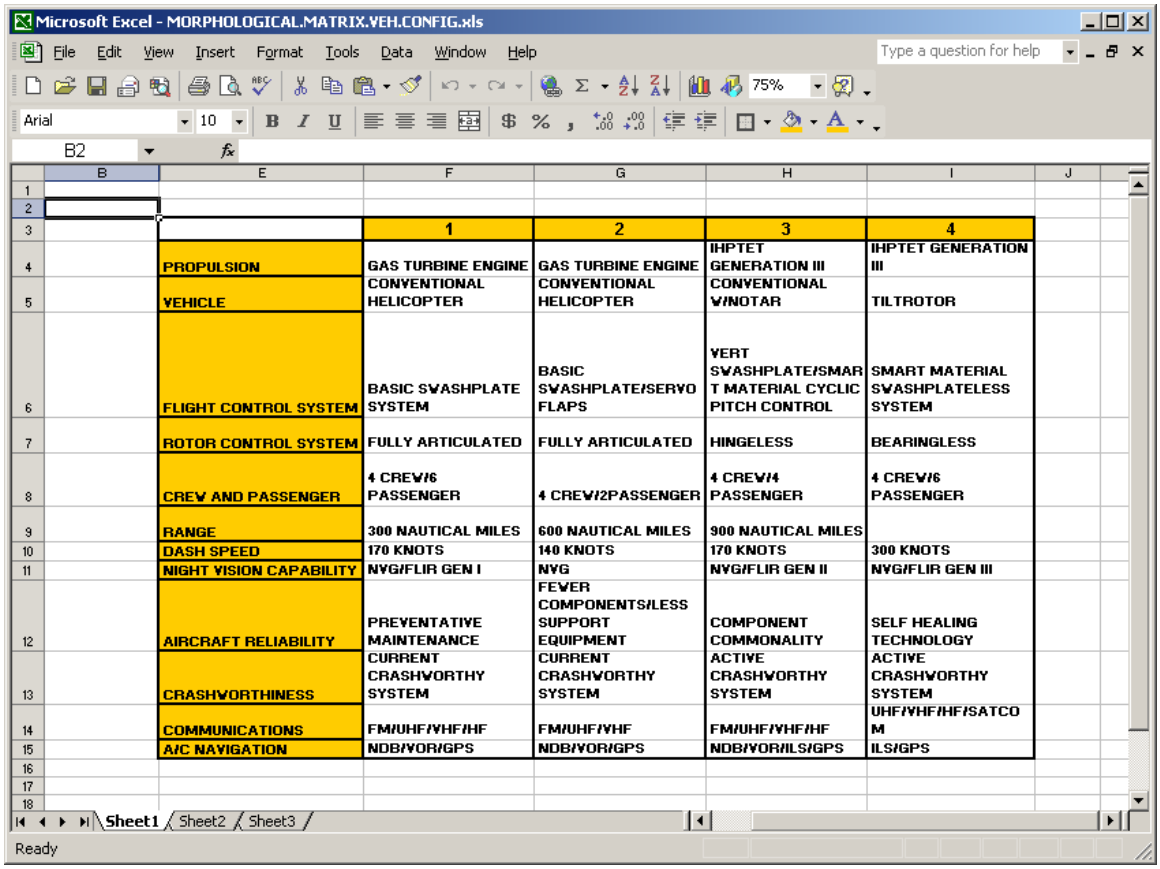
Eventually, there will be a decision making evaluation of the technology candidates. This will lead to a sort of Dr. Frankenstein Experiment by choosing all of the best components and combining them into a single "perfect design" for a vehicle. The challenge is then passed on to the engineering team, outside of the systems engineering phase, to homogenize the design and right size the components and interfaces. The evaluation of the competing functional characteristics is described fully in the next chapter of this thesis.

The morphological matrix of alternatives was used two times during the Kingfisher vehicle development example. The morph matrix was used for the first time to display the full range of vehicle configuration options that were available. In this use, the functional characteristics of several legacy vehicle systems were used to populate the body of the matrix.

The morph matrix was used a second time, during the brainstorming phase of determining an appropriate new flight control technology that would replace the use of the swash plate in the design, as defined in the AHS RFP. It is important to note that the functional characteristic population of the morph matrix in this second case consisted totally of very low TRL alternative technologies. Some of these were TRL=0. The second morph was also populated automatically as far as the engineering characteristics were concerned. However, this second set of engineering characteristics was distilled from the original full set of engineering requirements, with a focus on the Flight Control System (FCS) exclusively. This method of using the morph alternative matrix with a sub-set of

the original engineering requirements that have been defined in greater detail is typical of a complex product that incorporates advanced or cutting edge technologies.

The morphological matrix of alternatives is created in the MS Excel tool. The listing of the engineering characteristic groupings is made in the left hand column. The adjacent columns in the field are populated manually based on industry information, literature, and subject matter expertise. Each column of the field is commonly used to define the engineering characteristics of a given airframe system that is already in existence, or conceptualized previously. Displayed graphically in this manner, combinations of characteristics can be considered, which might not have been obvious otherwise. The engineering characteristics are populated into the morph from engineering requirement item types in TCSE. The grouping of airframe characteristics is populated from Building Block item types in TCSE. It is tedious to create the vehicle characteristics manually as building block items. However, they will be used multiple times after they are created, and so the effort is not wasted at all. The morphological matrix of alternatives is a purely visual tool, with little computational involvement. The computational aspects of this matrix will be discussed in the following Chapter.



	1	2	3	4
PROPULSION	GAS TURBINE ENGINE	GAS TURBINE ENGINE	IHPTET GENERATION III	IHPTET GENERATION III
VEHICLE	CONVENTIONAL HELICOPTER	CONVENTIONAL HELICOPTER	CONVENTIONAL W/NOTAR	TILTROTOR
FLIGHT CONTROL SYSTEM	BASIC SWASHPLATE SYSTEM	BASIC SWASHPLATE/SERVO FLAPS	VERT SWASHPLATE/SMART MATERIAL CYCLIC PITCH CONTROL	SMART MATERIAL SWASHPLATELESS SYSTEM
ROTOR CONTROL SYSTEM	FULLY ARTICULATED	FULLY ARTICULATED	HINGELESS	BEARINGLESS
CREW AND PASSENGER	4 CREW/6 PASSENGER	4 CREW/2PASSENGER	4 CREW/4 PASSENGER	4 CREW/6 PASSENGER
RANGE	300 NAUTICAL MILES	600 NAUTICAL MILES	900 NAUTICAL MILES	
DASH SPEED	170 KNOTS	140 KNOTS	170 KNOTS	300 KNOTS
NIGHT VISION CAPABILITY	NVG/FLIR GEN I	NVG	NVG/FLIR GEN II	NVG/FLIR GEN III
AIRCRAFT RELIABILITY	PREVENTATIVE MAINTENANCE	FEWER COMPONENTS/LESS SUPPORT EQUIPMENT	COMPONENT COMMONALITY	SELF HEALING TECHNOLOGY
CRASHWORTHINESS	CURRENT CRASHWORTHY SYSTEM	CURRENT CRASHWORTHY SYSTEM	ACTIVE CRASHWORTHY SYSTEM	ACTIVE CRASHWORTHY SYSTEM
COMMUNICATIONS	FM/UHF/VHF/HF	FM/UHF/VHF	FM/UHF/VHF/HF	UHF/VHF/HF/SATCOM
A/C NAVIGATION	NDB/VOR/GPS	NDB/VOR/GPS	NDB/VOR/ILS/GPS	ILS/GPS

Figure 6.7: Kingfisher Morphological Diagram for the SAR.IPPD selection of vehicle configuration. Hart, 2009.

It has been shown that the 7 MaP graphical tools could be used to sort requirements and requirements related data in preparation for analysis of alternatives. These tools help us to understand the true nature of the design concepts being developed, through investigation of their component functionalities in greater detail. Taken as standalone tools, the 7 MaP graphs do not provide a definitive design solution. Rather, they are a method to visualize the design solution space, where-in lies the desired vehicle system to meet the customer defined criteria. The digitization and integration of these 7

MaP tools through the application of COTS MS Office software only amplifies their utility in the system engineering phase of design.

The value of digitizing these tools allows for a great reduction in time and increase in accuracy associated with initial creation. In addition, the digital 7 MaP toolset can be dynamically linked directly to the requirement items in the requirement data manager. While having little value in the initial creation of the graphs, dynamic linking to the database has broader implications. It means that at any point in time, a change in the composition of the requirement item set, for whatever reason, can be immediately propagated to the all of the affected graphical tools and analysis sheets. This can be accomplished through a simple "Where Used" query in the Search function of the requirements data manager. It can also be accomplished through dedicated linking of the individual tool worksheets to the requirements set directly through a TCSE attachment item type to a resident folder. Through this functionality, the update of the tools is accomplished in less time, with greater accuracy. This is not possible with the employment of traditional IPPD methods using the 7 MaP tools on large posters with sticky papers.

Completely aside from initial creation and maintenance of the 7 MaP tools is the concept of template creation. Taken as a whole, the requirements and their associated 7 MaP tools could form a versioned set of data. This versioned dataset could easily be copied and pasted to create an entirely new requirements engineering project. This eliminates the time and knowledge constraints of starting from a stand still in developing a new project. This ability addresses the deficiency found in the Motivation section of this thesis, where paper based legacy knowledge content and 7 MaP tool data sets were

not available for re-consideration. The creation of a "rapid prototyping environment" through template generation for systems engineering of rotorcraft vehicle designs should not be overlooked. Although the creation of such a template is not detailed in this thesis, it is understood that this capability offers the capability to create strategic, knowledge-based assets that have a definable value to the manufacturing enterprise.

The utility of requirement item linking was briefly discussed in regards to updating the 7 MaP tools and analysis worksheets due to requirement changes. The link functionality forms a very powerful tool in the ability to provide bi-directional traceability among designated requirement item sets. Most obviously this would be used to provide a logical link between customer requirements and engineering requirements that directly satisfy them.

It is also possible to create a link between any two items that exist in the requirements data manager. The Trace Link utility is not limited to use with the requirement sets alone. The end linked data could be a technical report, an image, a powerpoint presentation, or even a Matlab script. Regardless of the nature of the item, through the trace link function, it can be logically related to any other appropriate item in the database. This provides an augmentation to the Search function that relies on dataset title or keyword search alone to locate the information. The Search tool offers an advanced, broad spectrum seek and retrieve capability and accomplishes a deep dive search even into the body text of documents. As such, the trace link function on the other hand satisfies the need to query based on "Where Used" allowing a search in-context for only the most relevant data. The link provides a more limited but focused query capability than the Search function.

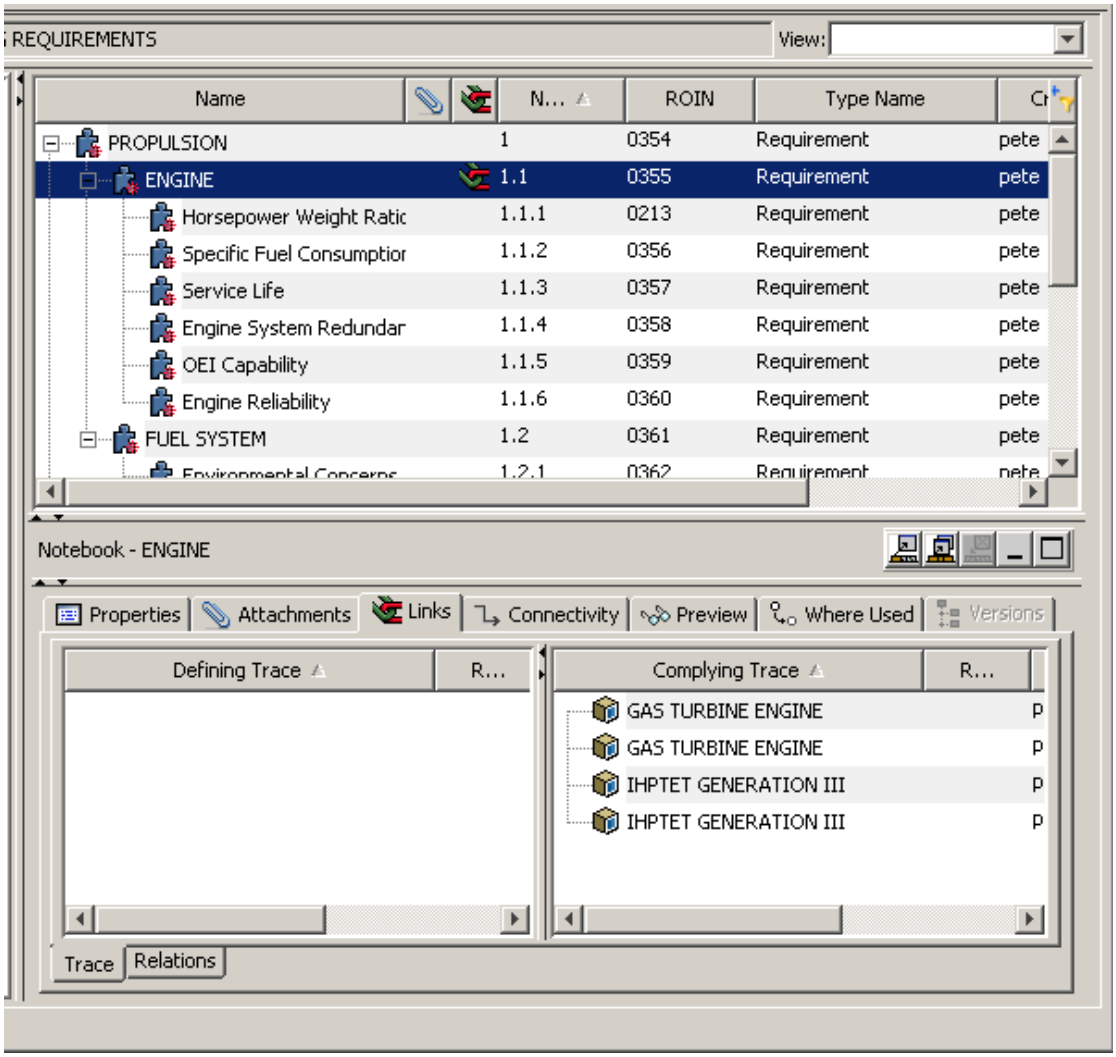


Figure 6.8: An example of Trace Link creation in TCSE between an engineering characteristic (requirement) and functional PSA building blocks. Hart, 2009.

CHAPTER 7

QUANTATIVE ANALYSIS

While the 7 Management and Planning tools discussed in the previous chapter provide an ability to visualize the qualitative data related to the system engineering phase of design, they are not strictly considered computational tools. A complementary set of quantitative tools exist to provide the necessary computational functionalities, based on the 7 MaP tools output. The quantitative tools are generally depicted as components of the Generic IPPD Methodology shown in Figure M.2. A more specific flow of the data through the quantitative tools is shown in Figure 7.1. This thesis does not purport that the tools discussed here are unique in performance of the discussed functionalities. The following tools will be used to illustrate one possible solution to product system concept definition.

The tools are:

Quality Function Deployment (QFD)

Pugh Matrix

Additional tools could be demonstrated at this point of the discussions, however, there demonstrative value in terms of TCSE would not be in excess of what is discussed for the QFD and the Pugh Matrices. Two tools would logically follow along in the IPPD methodology, Multi-Attribute Decision Making (MADM) and Technique for Order Preference by Similarity to Ideal Solution, (TOPSIS). While these tools remain strategically important to the completion of the IPPD methodology, they are not of great interest in relation to TCSE other than the previously stated integration of the Excel

sheets within TCSE. It is for this reason that the discussion will proceed without further mention of these two important tools.

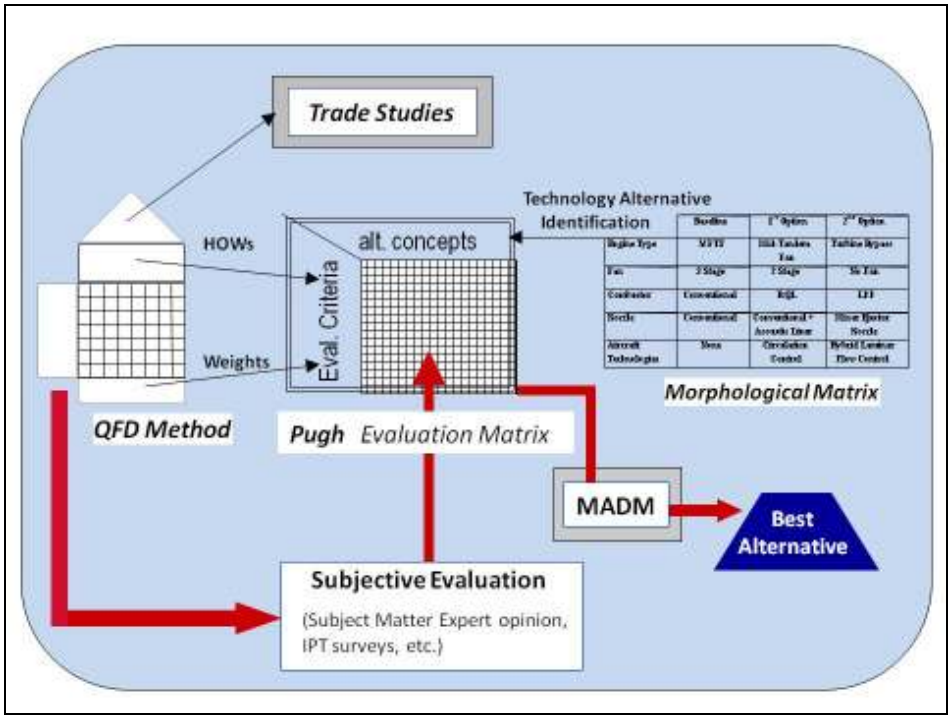


Figure 7.1 "Flowchart of Quantitative Requirements Analysis Tools featuring the QFD, Morphological Matrix of Alternatives, PUGH Matrix, and MADM tools." Aerospace Systems Design Laboratory (ASDL), 2008 [44]

Collectively, these tools form a baseline suite to enable the quantitative analysis of functional characteristic alternatives. They provide a set of computational tools whereby design concepts may be compared numerically. This is done to determine the clear superiority of a mix of technologies that will enable the customer specified design concept. The multiple design concepts are then comparatively analyzed to determine the best fit of systems and technologies to create a single physical product architecture.

QFD Method

The process begins with the definition of a matrix to conduct the Quality Function Deployment (QFD)[17] method, based on inputs from the 7 MaP tool outputs discussed in Chapter 6. As depicted in Figure 7.1, the QFD output is used in conjunction with the Morphological Matrix of Alternatives to populate the Pugh Evaluation Matrix, which will numerically distinguish between the alternative characteristics.

The QFD method is used to relate both the customer requirements and engineering characteristics on multiple levels in a single graphical tool. The relative ability and effectiveness of engineering characteristics to meet customer requirements is displayed graphically in the body of the graph. The QFD method incorporates the ranking of both customer requirement and engineering characteristic importance. A computational functionality is used to determine absolute and relative importance rankings. These are used downstream in the population of the Pugh Matrix. A comparison between a baseline product and existing product systems which meet the customer requirements provides a competitive assessment of the proposed product system.

The QFD method is often referred to as the “House of Quality” due to the general shape of the graphical tool as an elementary “house” with a pitched roof, consisting of “rooms.” A graphic of the QFD method is shown in Figure 7.2.

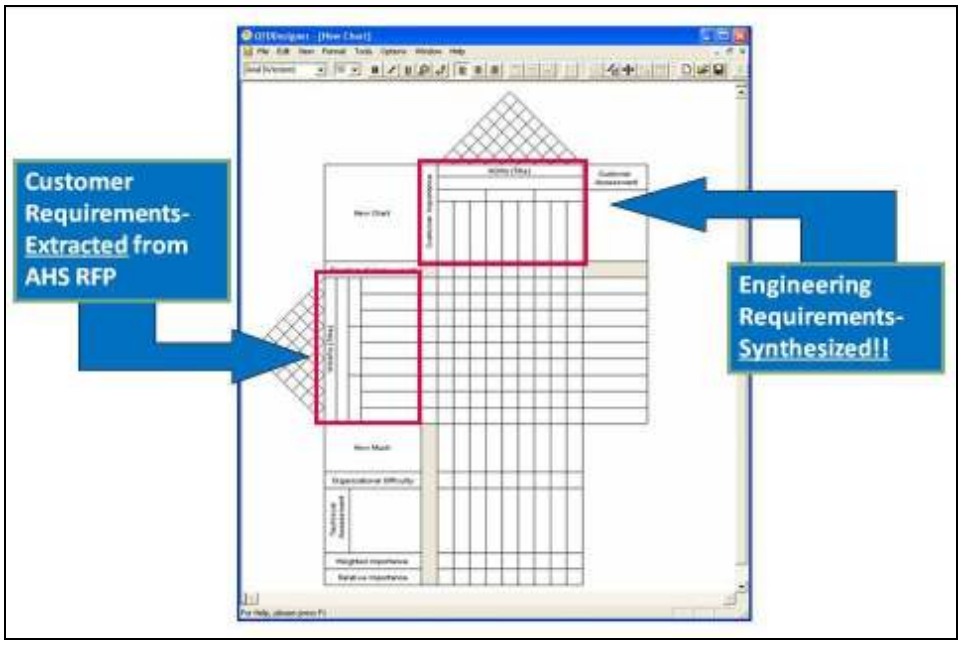


Figure 7.2: Blank QFD matrix showing house rooms and basic description. Hart, 2009.

The QFD tool is automatically populated from within the TCSE database. Using the Export function, the customer requirements and the engineering characteristics can be populated directly into the matrix. The requirements are exported as well as the group headings that were previously assigned in the Affinity diagram and captured into TCSE as Group Items. These form the core of the QFD method, defined by a vertical column of customer requirements on the left and a horizontal row of engineering characteristics across the top.

The body of the QFD (bounded by the left column and top row) is populated manually by the IPT. Consideration is made as to whether each of the engineering characteristics has a relationship to the customer requirements that is strong, medium, weak, or none. Numerical values are assigned to represent each of these designations in the Relationship Matrix section of the QFD method.

Trade studies are suggested through consideration of the inter-relationships among the engineering characteristics alone. This is depicted in the "roof" of the House of Quality. The roof is generally populated with graphical data to identify possible conflicting relationships among characteristics, rather than numerical data.

The main computational function of the QFD is to calculate the relative and absolute importance rankings among the customer requirements and engineering characteristics respectively. This data is depicted on the "floor" location in the "house" tool. A representation of the 2001 Kingfisher QFD matrix is provided in Figure 7.3.

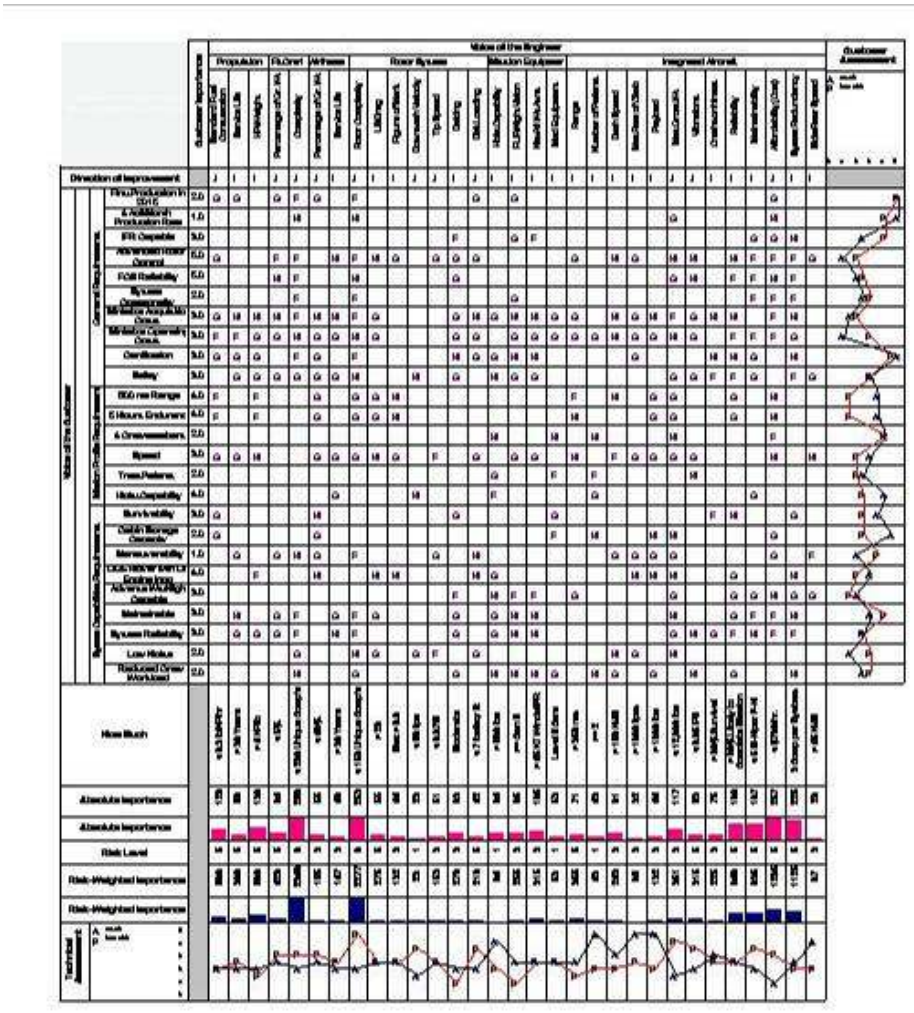


Figure 7.3: Original 2001 Kingfisher QFD matrix made inside of the QFD Designer standalone tool from Ideacore. [43]

The QFD method is not overly complicated in terms of calculations. However, it can be a tedious activity due to the multitude of diverse data sets depicted in the graph. Overall, the QFD method can be confusing to new users, who may under-estimate the impact that the results will have in defining a final compliant product system. This can cause mistakes in calculations, missed relationships, or over emphasis of trivial relationships. Each of these mistakes can and will skew the results of the QFD method, possibly towards an undesirable or dead end design concept selection downstream. It was shown in Figure 29 that the output from the QFD method will be used as the input into the Pugh Evaluation matrix. The effect of mistakes in the QFD will be carried through and amplified as the IPPD methodology is completed to support downstream lifecycle phases. Through digitization and automation of the QFD method, mistakes such as these can be avoided.

The digitization of customer requirements has been shown to allow for the automated export to a variety of related tools, including the QFD. The automated population of the QFD with customer requirements ensures that the complete set of requirements is being considered, with no omissions. The utility of the QFD method is greatly enhanced by the use of dedicated QFD software specifically designed for accommodating the requirements data and computations. The software that underlies the QFD method is not unique and can be created by an individual if they were so inclined. The choice of a COTS QFD tool can be more economical in the long run, especially if the IPT strengths do not include software development. In 2001, the Kingfisher IPT used a standalone QFD tool provided by Ideacore, Inc. called QFDDesigner. In the thesis

example, work done on the Kingfisher design, a COTS QFD tool, Triptych V 3.9, from Statistical Design Institute (SDI), was used.[45]

This particular QFD tool was chosen for the thesis example due to a development agreement with Siemens PLM Software to integrate Triptych seamlessly with Teamcenter Systems Engineering. The integration of any other tool of this nature is possible. The Triptych decision was made based on the ability to take advantage of the existing integration work done by SDI.

Nearly all standalone QFD software tools are simply MS Excel spreadsheets that have been created as templates to perform the QFD method graphics and calculations. The Triptych tool is no exception. Effectively, the QFD tool is a dedicated graphical user interface to MS Excel. Exporting TCSE data to the QFD method tool is the same thing as exporting the data to MS Excel. This allows the Triptych tool to leverage all of the functionality of the Microsoft Office productivity tools, as well as a very tight integration with the Teamcenter Systems Engineering environment. This includes the MS Office LIVE capability which will be discussed in Chapter 9 of this thesis. A depiction of the example Kingfisher vehicle QFD method data using the Triptych tool is provided in Figure 7.4.

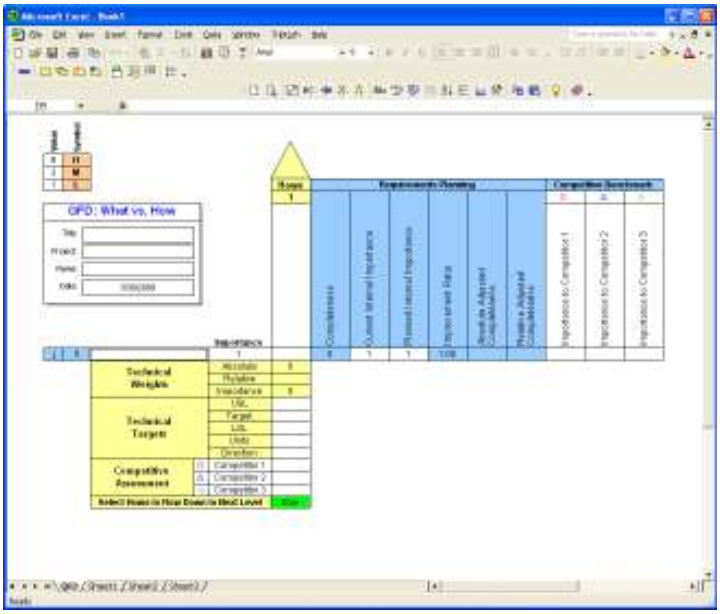


Figure 7.4: The QFD method matrix baseline inside of Tryptich.[45]

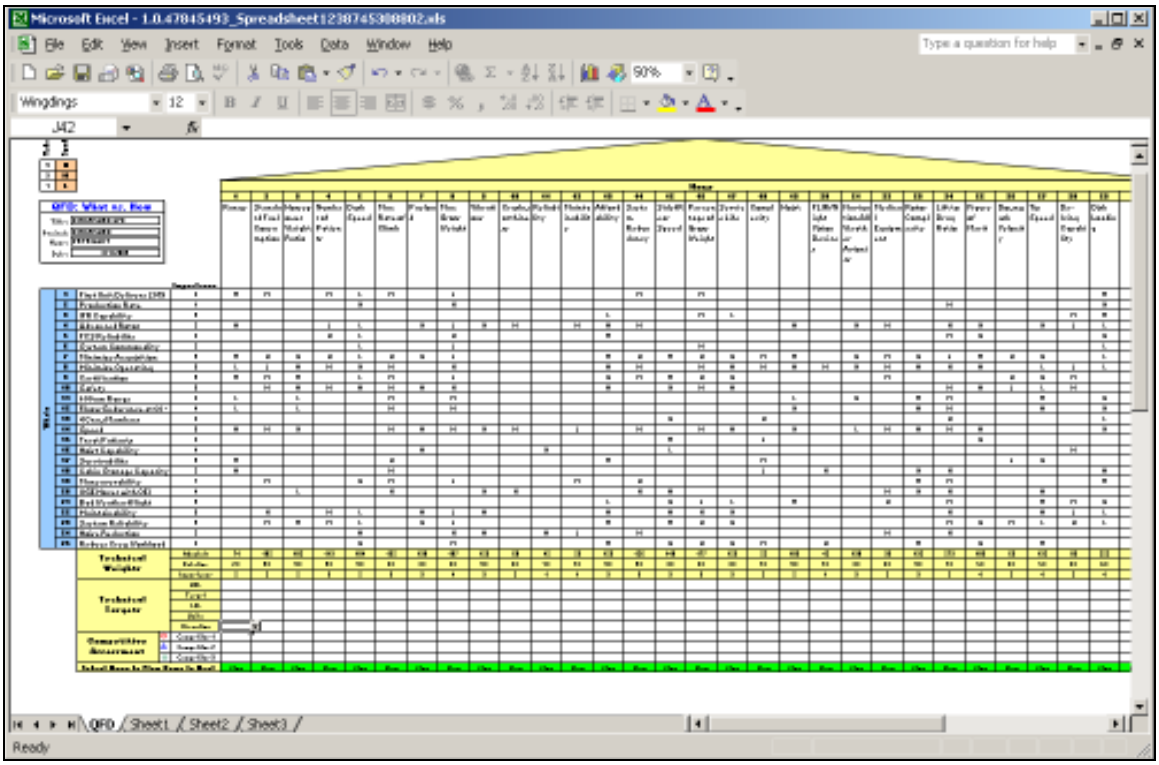


Figure 7.5: Kingfisher QFD matrix made inside of Triptych, based on data residing within TCSE. The relationship matrix is used to establish Trace Links in TCSE based on the existence of a relationship between customer and engineering requirements. Hart, 2009.

Examination of the "roof" of the house of quality provides guidance on which, if any, of the engineering characteristics are in conflict with each other. Conflicting characteristics may co-exist, however major conflicts must be resolved through further consideration before the IPPD method can proceed. Most of the conflicts can be resolved by increased information or through the conduction of trade studies to establish compromise positions. The trade studies are dictated by the roof of the QFD matrix, as shown in Figure 7.6. It would be most useful to the team for the trade study data to be attached to the QFD file to provide downstream support in the event of characteristic refinement. This eventuality should be expected and anticipated due to the evolutionary nature of complex systems, specifically rotorcraft vehicles. The relation of the Trade study to the QFD is accomplished through a Trace Link established within the TCSE tool. This marries the two documents, while maintaining integrations of both to the TCSE database elements.

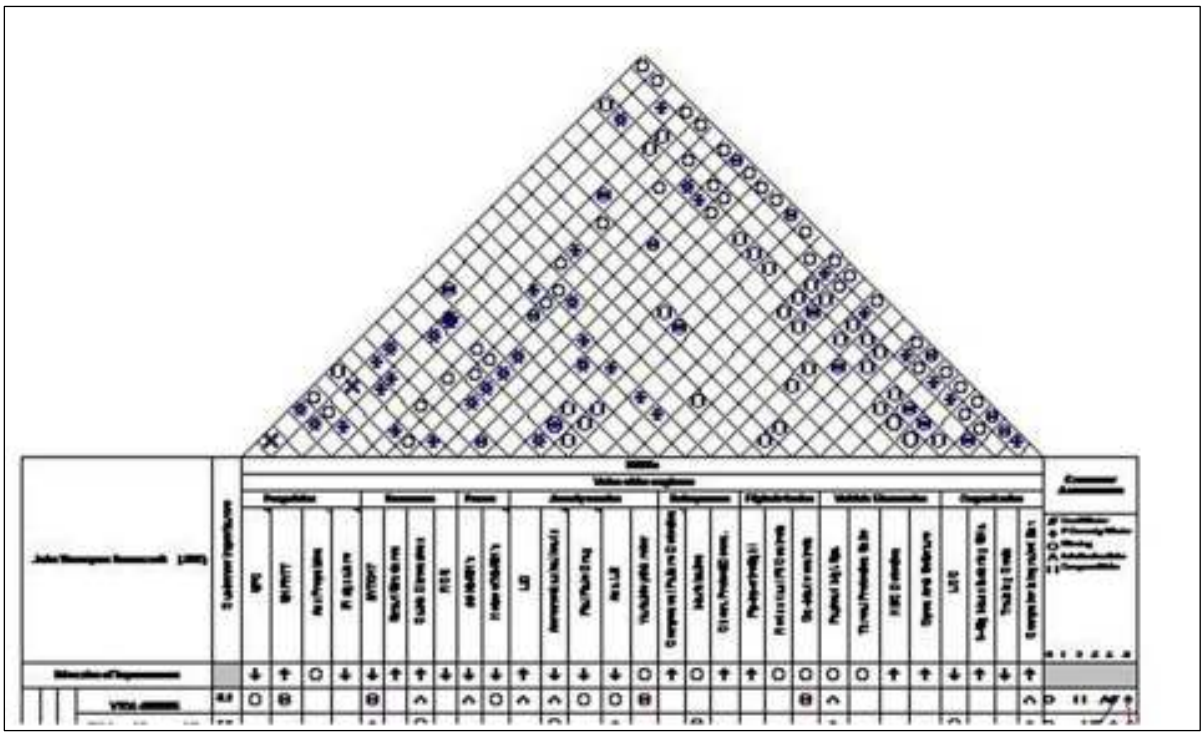


Figure 7.6: Kingfisher QFD method inter-relationship matrix for the "house" part. Providing guidance on the possible candidate trade studies that need to be performed. [43]

It is often necessary to perform multiple QFD methods for individual aspects of a single vehicle design. This would typically be necessary to investigate the design concept for future lifecycle phases: manufacturing, usage, and Maintenance/Repair/Overhaul. The need for additional QFD methods can also be triggered by the design team exploration of newly emerging technologies. In this case, distributed QFD would be more appropriate to collect the disciplinary or subsystem contributions to a main QFD matrix for the overall vehicle design. These could be any one, or multiple areas of improvement typified by low TRL values. Triggering examples include advanced flight control concepts for the Kingfisher, composite material design selection, or digital cockpit equipment selection and layout.

Each of these triggers would justify the creation of a new cascaded or distributed QFD method related to the main QFD. The new QFD is not made independently. Rather, it is created as a new QFD with a population of cascading information supplied by the main QFD. A depiction of Cascading QFD Methods is provided in Figure 7.7. A depiction of the distributed QFD Method is provided in Figure 7.8. Conceivably, the new cascaded QFD could be contained on a second spreadsheet within a single Excel workbook. However, it is a better practice to separate the cascaded QFD, in the event that it may be needed as a standalone template at some time in the future. The two QFDs (main and multiply cascaded) can be logically linked through the use of Trace Links in TCSE. This will ensure that if changes are made to the main QFD, the user will see clearly that changes may be necessary to the cascaded QFDs as well.

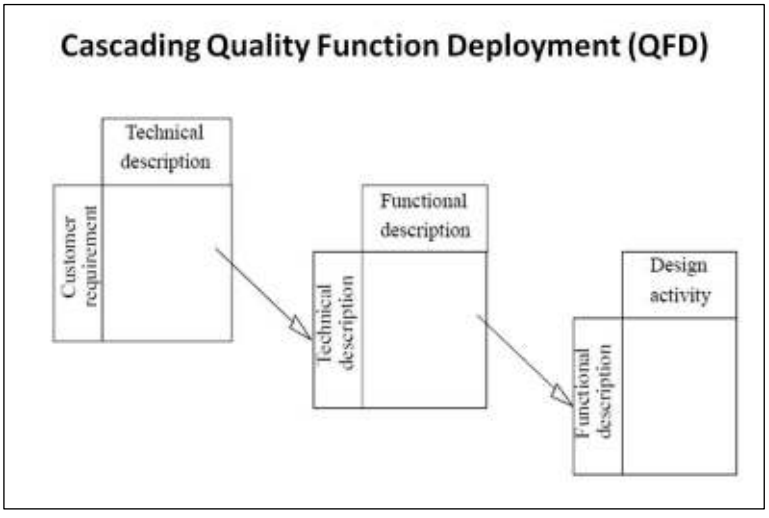


Figure 7.7: Cascading QFD Matrices. [17]

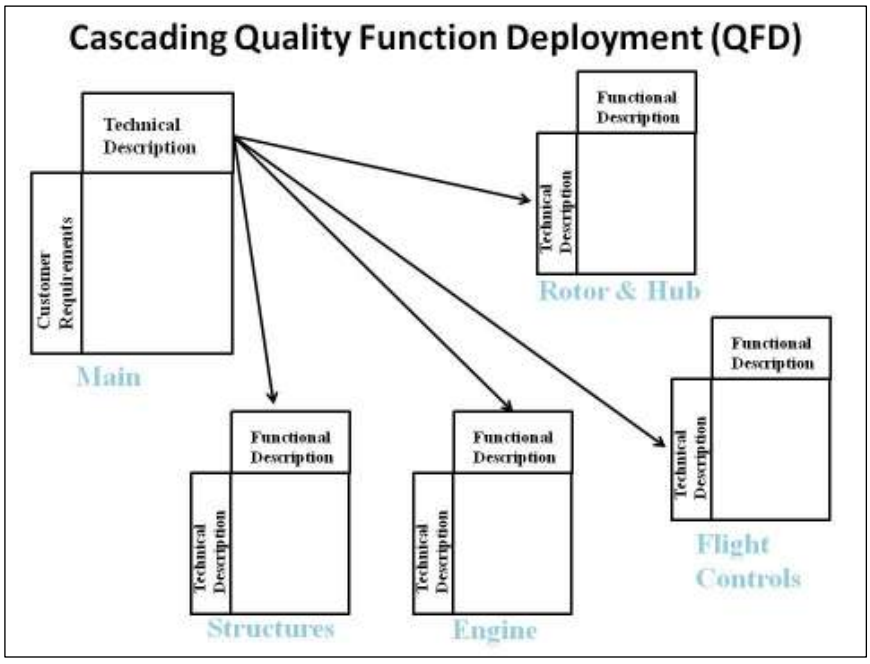


Figure 7.8: Distributed QFD with Primary and Secondary (Disciplinary) Matrices. Hart, 2009.

It is possible for the data to automatically update to the cascaded QFD using the Excel Live function. However, extreme care should be used in employing this capability. It is common for users to make changes to datasets, with the changes having unexpected (and unseen) effects on analysis tools that may be dynamically linked through a Live link. It would be prudent for the average user to provide logical links among datasets and tools in the TCSE database, rather than automated updating. This will avoid the situation of lost data through unanticipated rewrites of data sets within interdependent analysis tools, such as the QFD and Pugh Evaluation Matrix. Advanced users who are veterans of the TCSE tool would no doubt want to automate and Live interlink as many tools as possible. This would allow a change in customer requirements made in a QFD matrix to propagate up to the TCSE database items, out to the 7 MaP tools, and down to the Pugh

matrix. This leverages the bi-directional traceability of the TCSE environment to reduce the time and cost of manual updates for advanced users.

Pugh Evaluation Matrix

Once the QFD method has been accomplished, the Pugh Evaluation Matrix is used to synthesize and downselect a product functional architecture. [17] The Pugh matrix is a decision support tool, which iteratively compares product design concepts against a baseline concept in order to develop a "best candidate" design concept. The iterative nature of the Pugh matrix suggests the use of the knowledge capture and management capabilities in TCSE. This is accomplished in TCSE by revision control through versioning, with the archiving of intermediate versions as database items. In the event of the existence of multiple design decisions, there would be multiple Pugh matrices, each used iteratively to synthesize the best functional system architecture.

As shown in Figure 7.9, the Pugh matrix "core" is populated from output of the Morphological matrix of Alternatives, and the QFD method. The QFD method provides the Comparison Criteria, generally retrieved from either the customer requirements or the engineering characteristics, but not a mix of both. The comparison criteria populate the left column of the Pugh matrix.

The Design concepts from the Morphological Matrix of Alternatives are copied over to the top row of the Pugh matrix to populate the Design Concepts. The results of a manual team exercise to compare the design concepts to a selected baseline design concept are populated into the body of the matrix. A numerical summarization of the comparative analysis results is contained in the lower portion of the Pugh matrix.

The implementation of the Pugh Evaluation matrix in Teamcenter Systems Engineering is very similar to the tools that have been discussed in the thesis. The Pugh Evaluation Matrix is best suited to be produced in a Microsoft Excel spreadsheet. Dynamic linking to both the QFD and Morphological Matrix would be desirable. This is most easily accomplished through the creation of the morph matrix of functional design concepts as Functional Building Block Items within TCSE. The components of the design concept building blocks can be re-arranged through successive versioning. An example of this technique is depicted in Figure 7.9.

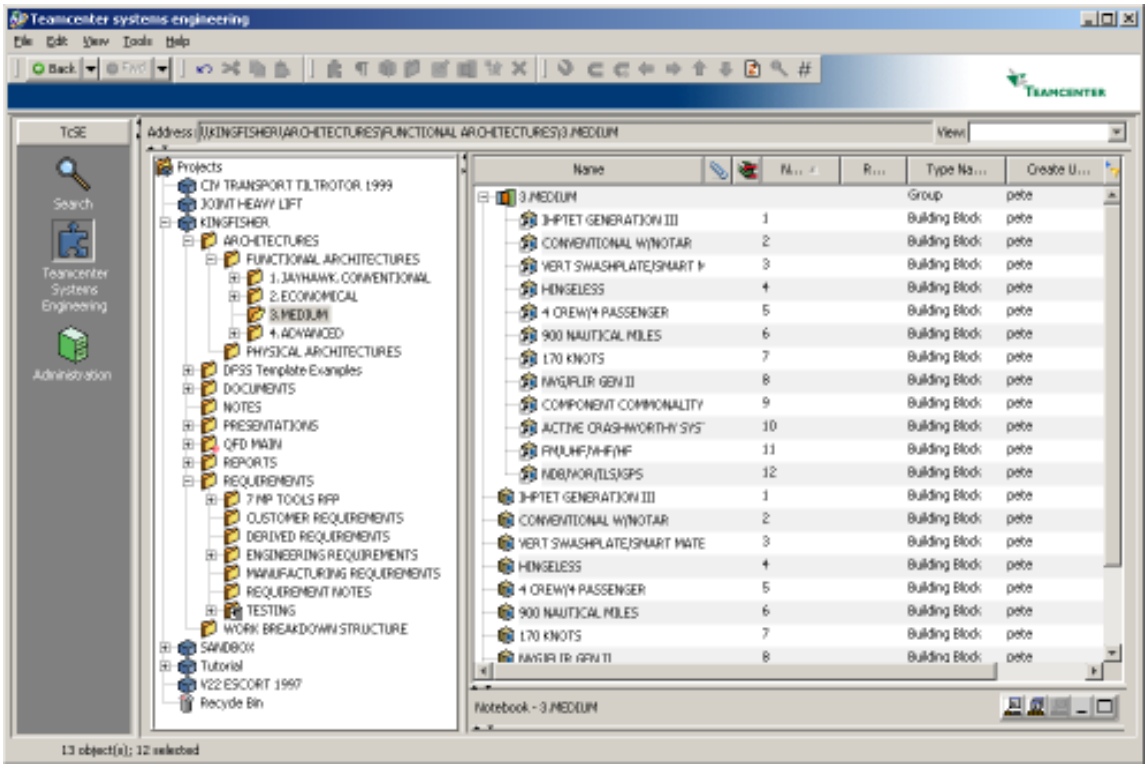


Figure 7.9: Screen grab of TCSE showing Functional Building Blocks developed for the Design Concepts used in both the Morphological Matrix of Alternatives, and the Pugh Evaluation Matrix. Components of the design concepts are depicted as hierarchical items, arranged through numbered and indented building blocks, contained in a dedicated folder. Hart, 2009

Ordinal Scaling was used in the illustration of the Pugh matrix with the Kingfisher vehicle example. This choice of scaling used mathematical symbols (+, -, S) in the comparative matrix to express relative merit of each design concept candidate, iteratively compared pair-wise. An Interval Scale could have been employed, where a numerical assignment is made for the results of the pair wise comparisons. The ordinal scale was seen as efficient to use for the basic investigations of the academically based Kingfisher vehicle design. In the case of a commercial grade investigation, where design concepts are not so easily differentiated, the Interval scale would provide enhanced utility.

The Pugh matrix was used two times during the system engineering for the Kingfisher vehicle design. First it was used to determine the overall vehicle configuration of the rotorcraft system (tandem, single, tiltrotor, coaxial…). The second time was used to determine the most appropriate advanced on-blade flight control system. The vehicle configuration options were listed based on existing technologies employed in real world fielded systems. The characteristic alternatives for the advanced flight controls were listed from a review of design concepts that are only in the concept stage of development and not fielded.

Pugh Matrix Configuration Selection			Alternative Concepts		
			BASELINE HH-60	1 Advanced Helicopter	2 Tiltrotor
AFFORDABILITY	Performance	Range	DATUM CONCEPT	0	1
		Endurance		1	1
		Cruise Speed		0	1
		Maneuverability		1	1
		Reliability		0	0
	Feasibility	Vehicle Size		0	1
		FCS Complexity		-1	-1
		Vehicle Complexity		0	-1
	Costs	RDTE		-1	-1
		Production		0	-1
		Operation		0	1
			Σ + 1	**2**	**6**
			Σ - 1	**2**	**4**
			Σ 0	**7**	**1**

Figure 7.10: 2001 Kingfisher IPT Pugh matrix used for the overall vehicle configuration alternative down select. [43]

Pugh Matrix Civil Search and Rescue Tiltrotor			Alternative Concepts			
			BASELINE Heliflap Elevon	1 Electric Blade Root Actuator	2 Piezo-Pneumatic System	3 PZT Modulated Blowing
AFFORDABILITY	Performance	Frequency Response	DATUM CONCEPT	-1	-1	1
		Induced Drag		1	0	1
		Profile Drag		1	0	1
		Cruise Effectiveness		1	0	-1
		Hover Effectiveness		0	0	1
		Control Authority		1	0	1
	Feasibility	Scaleability		0	1	0
		Weight		-1	0	0
		TRL		-1	0	1
	Costs	Total System Complexity		-1	0	0
		RDTE		-1	0	0
		Operation		-1	0	0
		Reliability		0	-1	-1
			Σ + 1	**4**	**1**	**6**
			Σ - 1	**6**	**2**	**2**
			Σ 0	**3**	**10**	**5**

Figure 7.11: 2001 Kingfisher IPT Pugh matrix used for the advanced flight control system alternative down-selection. [43]

The TCSE environment depicted in the previous figures represents a great leap forward in technology available to perform the QFD and Pugh evaluations. This can be demonstrated easily by referring to the initial design experience with the Kingfisher. The initial evaluation of the vehicle configuration resulted in the single main rotor being selected. Upon further review, the decision was found to be skewed by the point of view of the IPT itself. Most of the team were UH-60 pilots. They felt confident that the UH-60 configuration would be able to meet the mission requirements, given some appropriate technology improvements.

In a second consideration of the Pugh matrix, additional information was made available to the team on the capabilities of the tilt rotor configuration, specifically cruise speed. It is for this reason that the second consideration of the Pugh matrix for the Kingfisher resulted in a tiltrotor configuration as the best possible technology option. The decision was a normal occurrence in designs: re-evaluation based on an increase in product knowledge. But this created the need for a re-evaluation of the advanced flight control system concepts. This was needed due to the limitations placed on which FCS were applicable to a tiltrotor hub verses a conventional single mast hub.

The second evaluation of the Pugh used the same criteria and the same design concepts as the first Pugh. However, due to the nature of the manual implementation of the IPPD process at the time, it still took considerable time to re-run this analytical tool. In addition, the Pugh for the FCS had to be partially re-considered. The recommended deployment of the TCSE environment would have greatly enabled the retrieval of the first Pugh, for re-evaluation, and integration into the overall IPPD for the Kingfisher.

CHAPTER 8

PRODUCT STRUCTURE ARCHITECTURES

Functional Product Structure Architecture

Following their synthesis in Chapter 5 engineering characteristics were used in the QFD method to evaluate relation to the customer requirements, and provide a basis for prioritization. Following these activities, the IPT is ready to begin proposing candidate functional product structure architectures (PSA) that may complement the engineering characteristics to some extent. While generally a good fit, it is often apparent that a single vehicle concept functional PSA will not contain all of the engineering characteristics of a given vehicle design. It is for this reason that the Morphological Matrix of Alternatives and the Pugh Matrix were used in Chapter 7 to evaluate the fit of existing functional architectures, and propose new architectures as necessary to more adequately reflect the engineering requirements.

Both functional and physical product structure architectures are composed of elements which reside in TCSE as the Building Block item type. The building block item type is also used to represent components of the WBS, which will be discussed shortly in this chapter. The building block item type can be customized in TCSE to distinguish between functional and physical architecture building blocks, through different icons and properties. This was not done in the Kingfisher TCSE example environment, due to the stated goal of deploying the tool in an out of the box manner.

The Group item type is used in TCSE to arrange the building blocks associated with a given vehicle design concept. The Group item type does not act as a container for

the building blocks. Instead, it simply associates multiple building blocks with a name representing the vehicle design concept. As with all use instances of the Group item type, a single building block may be enrolled in multiple Groups. This is a common occurrence.

The functional PSA building blocks are created manually in TCSE, however, this process can be greatly enhanced through the use of Excel spreadsheet. It is often tedious to work in TCSE on a line by line basis. Many engineers work much more rapidly in Excel, especially during data input. This is helpful, because a created Excel sheet may be brought into TCSE through the import function and used to populate the functional building blocks. This has actually been identified as a TCSE best practice by Siemens PLM Software instructors.

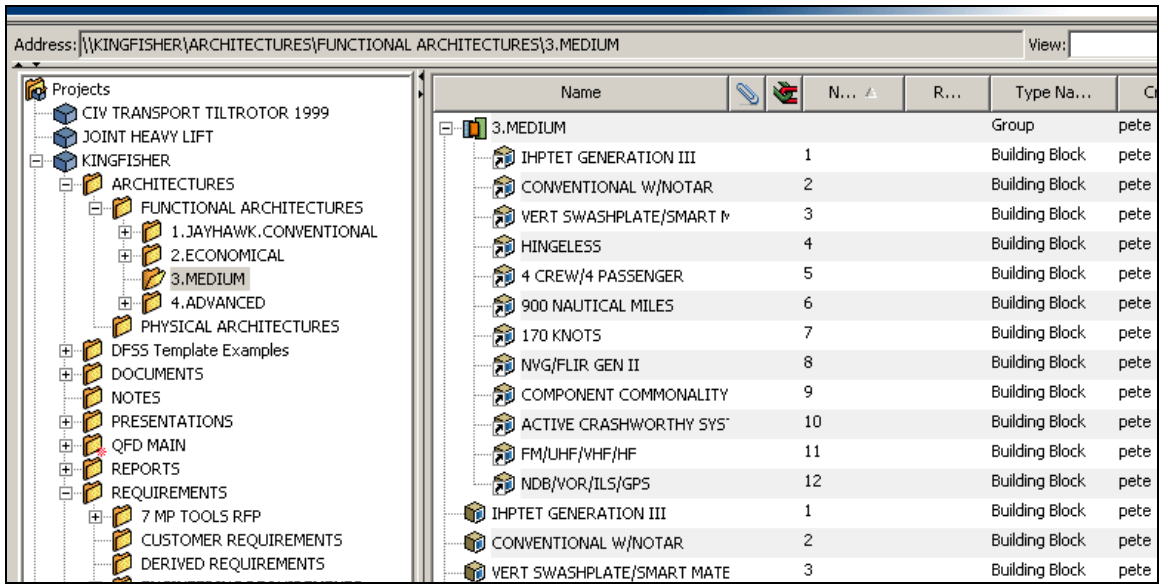


Figure 8.1: Functional Building Blocks defined for a candidate vehicle design concept. The use of the Group item is shown as an identifier for the concept. Hart, 2009.

The functional PSA components are used to populate the main body area of the morphological matrix of alternatives. This is accomplished though the export of vehicle design concept-candidate functional component building blocks into an Excel Template. Additional building blocks are used following the analysis and down select of the best candidate vehicle design concept. The best candidate vehicle design concept may not be a real system that exists today. It is generally likely that the best candidate system is a hybrid consisting of components from several individual systems. In this case, a new Group item type would be created for the hybrid design concept, and the heterogeneous components building blocks would be related.

In the case of the Kingfisher example vehicle, a hybrid design concept was necessary, and eventually created by the IPT. This consisted of the best components of the Medium Technology levels applied to a tiltrotor vehicle configuration, rather than a conventional helicopter vehicle configuration.

Work Breakdown Structure

A WBS is used to define the program that will realize the vehicle system concept developed in the systems engineering phase of design. As such, it represents an output of sorts for the system engineering phase in advance of the detail design and analysis work associated with the engineering phase. Because the WBS is used in industry and government as both a project management tool and a contracting tool, a substantial body of work exists to standardize usage and increase uniformity associated with the creation and use of the WBS. The WBS depicts the hierarchical decomposition of the newly defined vehicle system in a graphical manner. The typical graphical tool used to depict

the WBS is a Tree Diagram. However, the WBS could be expressed as a numbered listing of nested product components and sub-components, as long as the hierarchy of the product is maintained. The WBS is a product-centric tool, although it is derived from systems engineering through functional architecture downselect.

"The WBS is (formally) defined as: *-A product-oriented family tree composed of hardware, software, services, data, and facilities. The family tree results from systems engineering efforts during the acquisition of a defense material item.* *-A WBS displays and defines the product, or products, to be developed and/or produced. It relates the elements of work to be accomplished to each other and to the end product.* *-A WBS can be expressed down to any level of interest. However the top three levels are as far as any program or contract need go unless the items identified are high cost or high risk. Then, and only then, is it important to take the work breakdown structure to a lower level of definition."*

Table 8.1 Work Breakdown Structure Formal Definition. [46]

The goal of the WBS is to provide a listing or diagrammatic tool composed of the component parts and assemblies necessary to achieve the stated mission profile at the levels of performance prescribed by the customer need statement. The WBS is routinely developed as the end result of the systems engineering process, in anticipation of downstream engineering activities. The WBS needs to exhibit the decomposed hierarchy of the proposed (vehicle) product system, so that technical schedule and cost data may be made available and consumed by decision making authorities.

The goals of the WBS are accomplished by defining the logical relationships between all elements of the physical system architecture and related appliances. This is

generally done to three levels of indention with lower levels typically assigned for high risk or high cost programs. There are a number of Common WBS Elements that are applicable to nearly all DoD-based systems. They are listed below and depicted graphically in the 2001 WBS graphics associated with the Kingfisher example vehicle design concept.

-Integration, Assembly, Test and Checkout **-Systems Engineering and Program Management** **-Training** **-Data** **-System Test and Evaluation** **-Peculiar Support Equipment** **-Common Support Equipment** **-Operational and Site Activation** **-Industrial Facilities** **-Initial Spares and Repair Parts** As well as hardware and software that defines the specific capability of the product. In the example case of the Kingfisher these are: **-Aircraft System** **-Electronic/Automated Software System**

Table 8.2: Common Work Breakdown Structure Elements for Aircraft Systems. Source: MIL-HDBK-881, DoD Handbook – Work Breakdown Structures for Defense Materiel Items, January 2, 1998. [46]

It is common for a WBS to be established for a product system to three levels[46]. Each of the levels will typically increase in population the higher the WBS level identifier. The top three levels are typically specified as:

LEVEL 1: The entire product system under consideration. This is a top level descriptive identification of the system, usually consisting of a single entity. The Program name or Project vehicle system identification usually populates Level one.

LEVEL 2: The major elements of the product system. For an aircraft, this would typically involve the major geometric items and systems of items required for full system capability. It is important in this age to include both hardware and software elements and accumulative system level identifiers, including data and services.

LEVEL 3: The product system elements that are components of the Level 2 elements. These would include types of sub-systems, types of data sets, types of services, and sub components of major system assemblies.

The 2001 Kingfisher Vehicle concept WBS is depicted in Figure 8.3, Figure 8.4. The Kingfisher WBS was carried out to Level 4 in some areas, specifically the aircraft system. This was due to the increased complexity of the aircraft system in relation to all of the other systems associated with the Vehicle concept physical architecture. Special attention was visited upon the Flight Control System as this was determined early by the team to be a high risk sub-system of the Kingfisher vehicle.

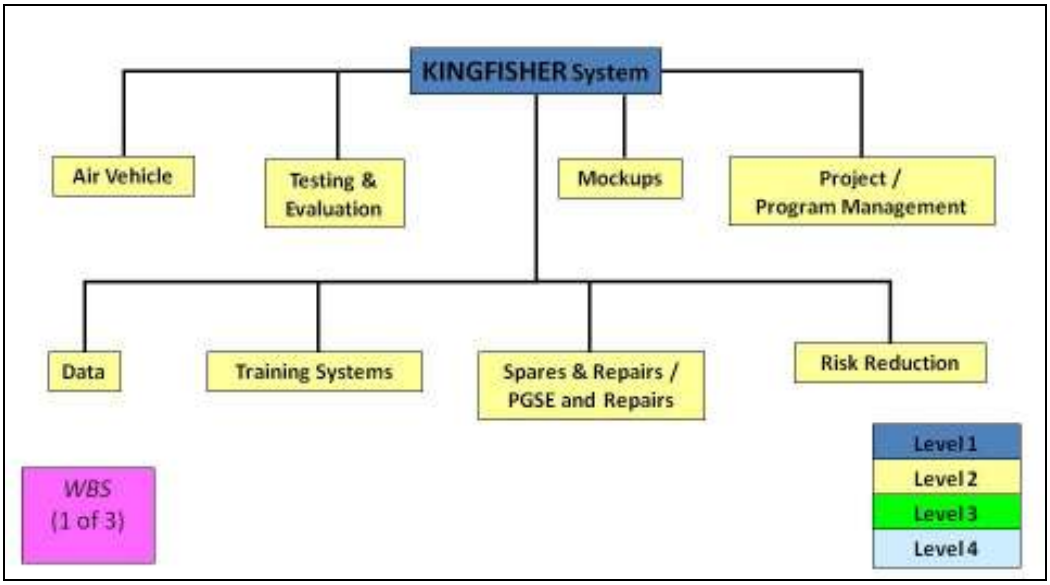


Figure 8.2: 2001 Kingfisher IPT Work Breakdown Structure, depicted as a static image in MS Powerpoint. WBS is shown at Level 2. [43]

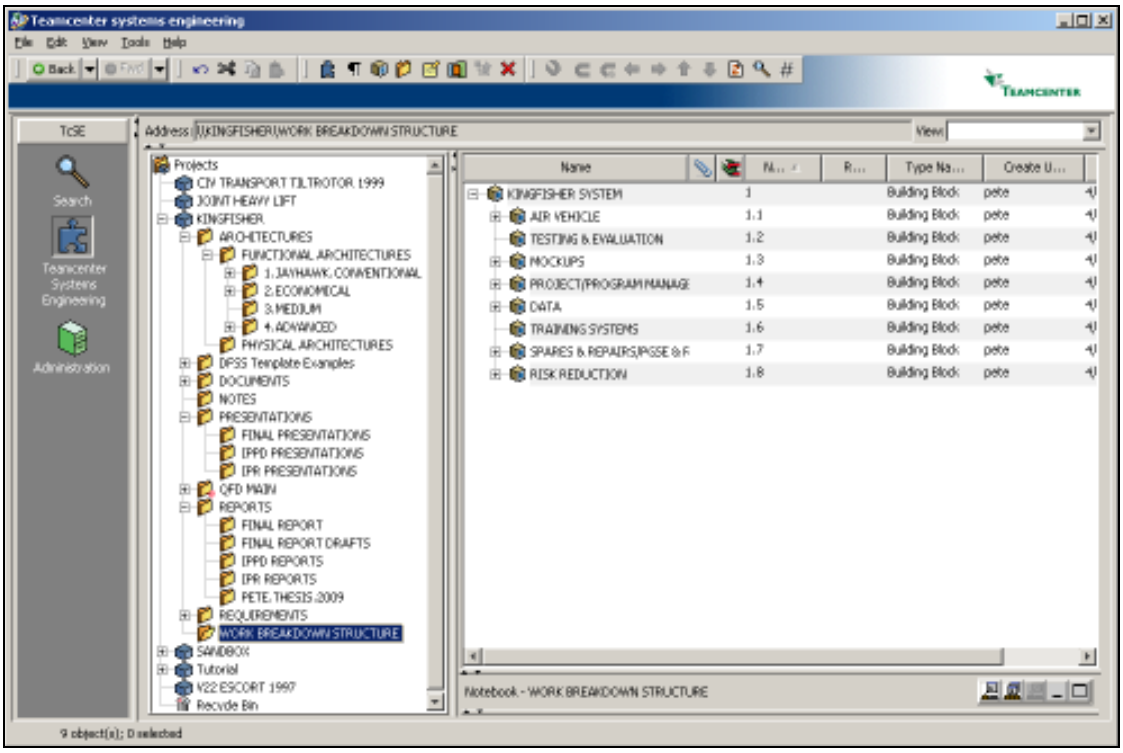


Figure 8.3: TCSE showing Work Breakdown Structure composed of Building Block item types for the example Kingfisher Vehicle Concept. WBS is shown to level 2. Hart, 2009.

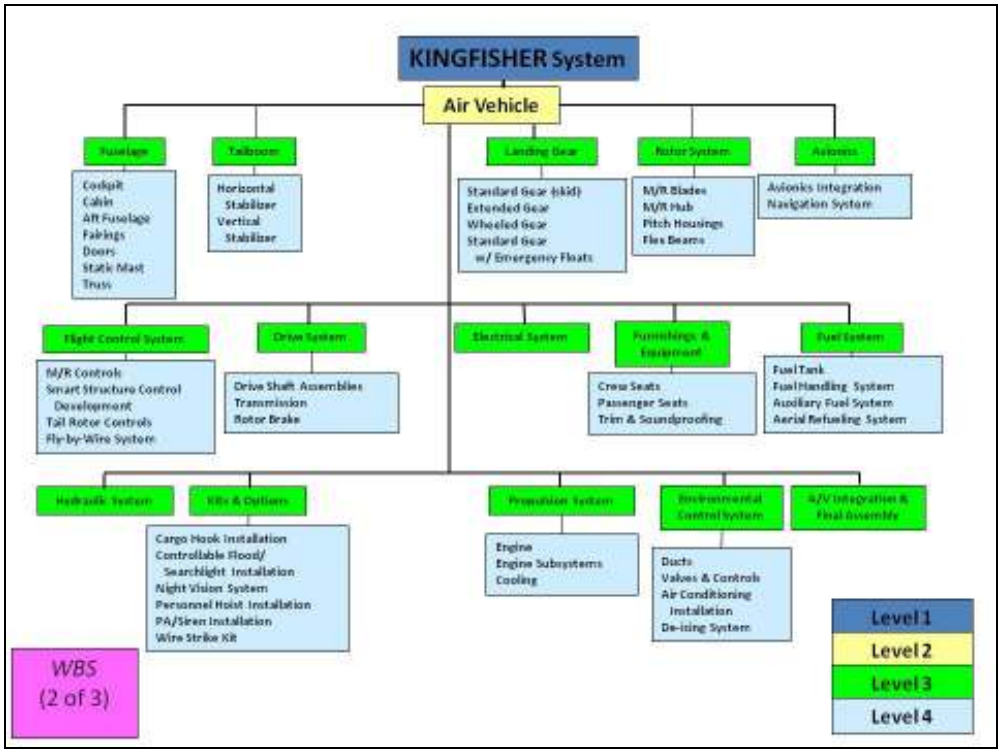


Figure 8.4: 2001 Kingfisher IPT Work Breakdown Structure, depicted as a static image in MS Powerpoint. WBS is shown at Level 4. [43]

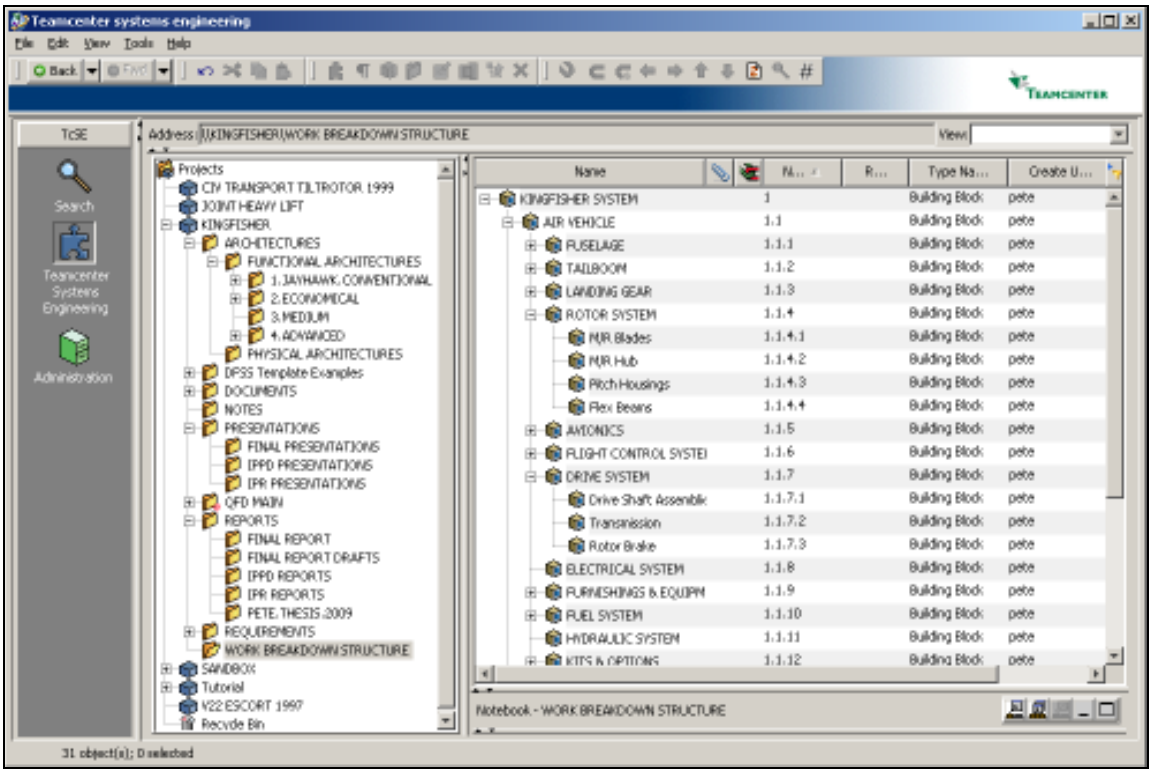


Figure 8.5: TCSE showing Work Breakdown Structure composed of Building Block item types for the example Kingfisher Vehicle Concept. WBS is shown to level 4. Hart, 2009.

WBS Synthesis from TCSE Eng Reqts.

In TSCE, the WBS is represented as a listing of numbered, hierarchical product sub-components. There is a dedicated TCSE database Item Type for creating all architectures and the WBS called a "Building Block." The Building Block is used to represent a wide variety of decompositions including Functional decomposition, Physical Components, Work Breakdown Structure, Organizational Charts, etc. A depiction of the Kingfisher Vehicle WBS in TCSE, using Building Blocks, is shown in Figure 8.6.

The WBS can be more easily displayed graphically through the use of the MS Visio Live functionality. This provides a more readily understood diagram form of the WBS, but contains the same data as the building blocks in TCSE. The Visio diagram is

created through the export function based on the children of a selected parent object. In the case of the thesis example, the Kingfisher Vehicle System is chosen as the parent object. Visio stencils must be prepared in advance to be compatible with the TCSE data models. TCSE is provided with several basic Visio stencils to accomplish the large majority tasks associated with general use.

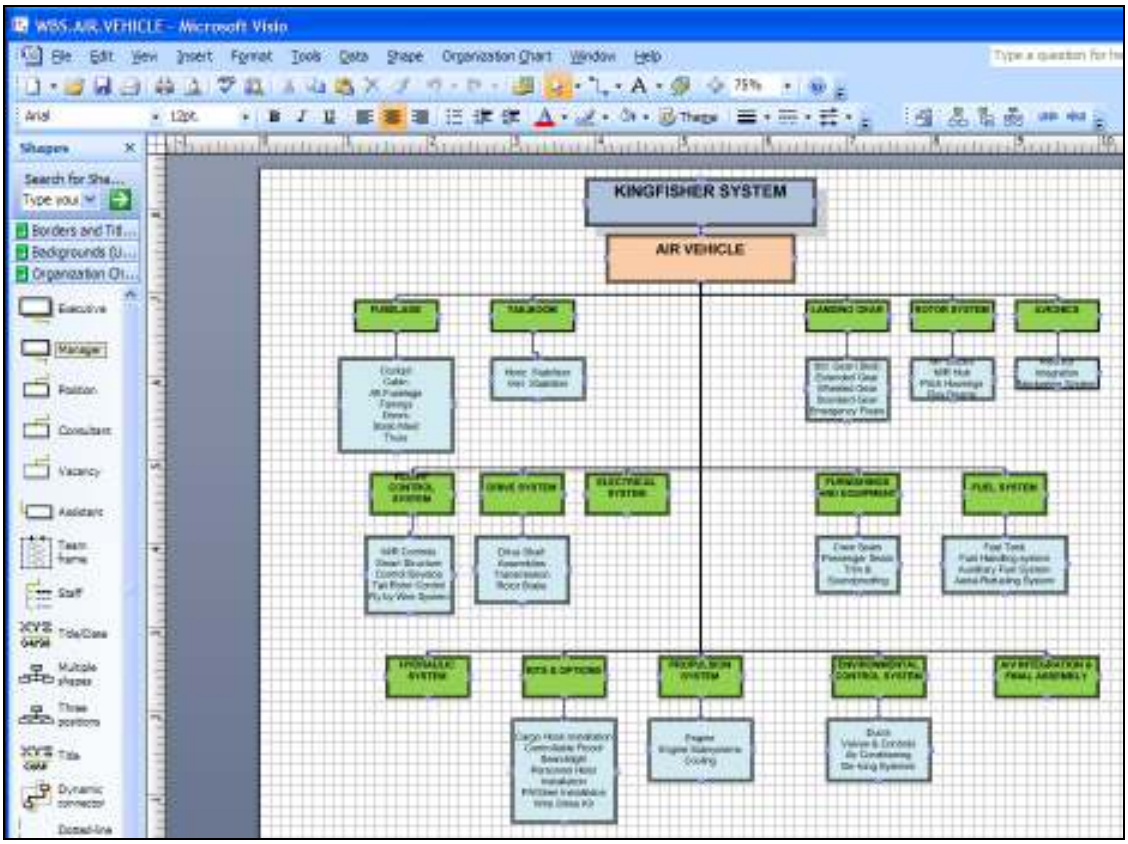


Figure 8.6: Work Breakdown Structure for the example Kingfisher Vehicle Concept, as depicted in the MS VISIO tool. Hart, 2009.

Trace Links-Requirements to Functional Architecture

Trace Links are used to create relationships between the Requirements data items and the Functional Architectures building block items. The relationship established is usually one of compliance or satisfaction. In this regard, it may be necessary to map

multiple requirements to a single architecture or individual requirements to multiple architectures. This creates multiple combinations of Trace Link strategies as 1:1, 1:N, or N:1.

Trace Links-Functional Architecture to Work Breakdown Structure.

As was discussed with the flow down of requirements to Functional Architectures, Trace Links are used to relate the building blocks that define the functional architecture to building blocks that define the Physical Architecture. This is done to provide bi-directional traceability between the building block sets. The thoughtful establishment of Trace Links can also provide an analysis capability through the examination of building blocks that are orphans, or requirements that have no children.

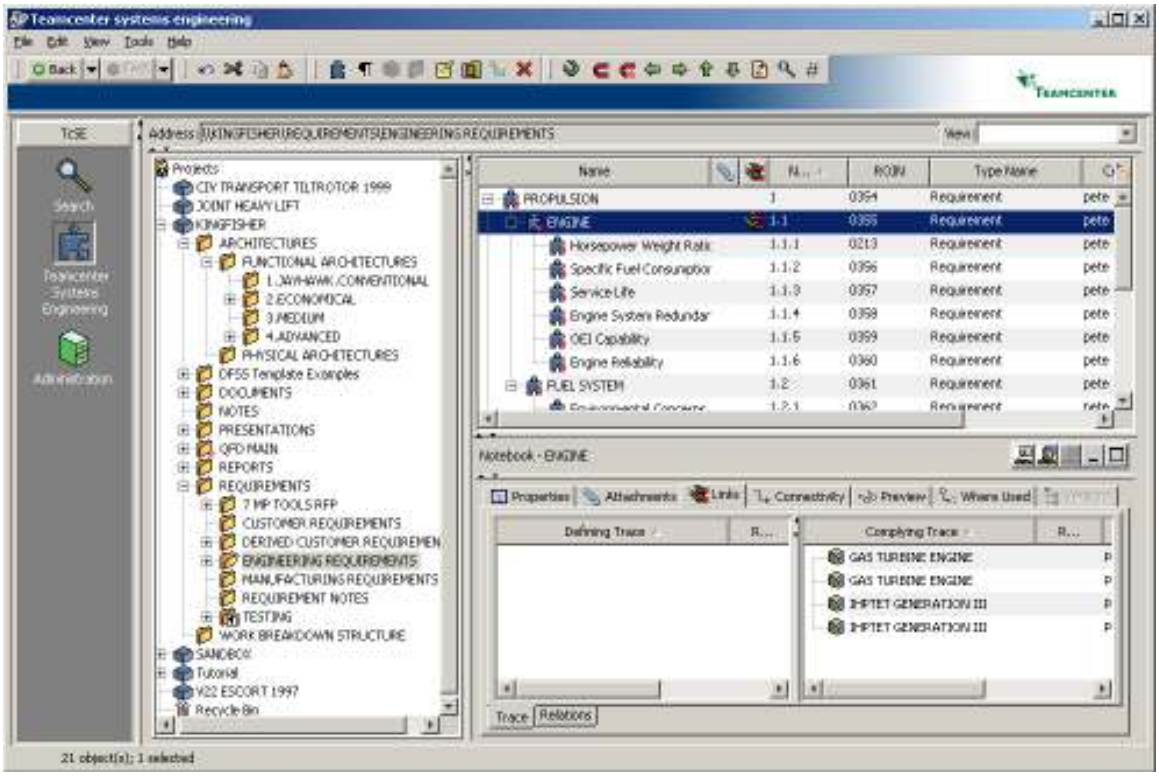


Figure 8.7: TCSE showing Trace Links created between Engineering Requirements and the Functional Building Blocks residing in candidate vehicle systems. Hart, 2009..

The Building Blocks used to define the WBS can be made individually through a manual function or semi-automatically through the use of the Trace Link creation function. Rapid creation can be accomplished through the Copy/Paste functions (ctrl+c, and ctrl+v). In addition, the building blocks could be created in an MS Excel Live spreadsheet and imported into TCSE. Often it is quicker to define objects of this nature using the integrated tool, due to user familiarity with the Microsoft Office products. Regardless of the original creation method, the building blocks can be subsequently promoted or demoted in the hierarchical order, given the proper role permission. Once created, the building blocks are assigned a Numerical Identifier which would naturally correspond to the Level of the building block in the hierarchical order. This is clearly shown in Figure 8.5.

CHAPTER 9

TOOLSET INTEGRATION

It is most desirable to use a single software tool to accomplish all the needs of a systems engineering analysis. This would be effective in reducing overall software costs and eliminating the need for often complex integrations. Software Toolsets have a tendency to be similar to Swiss army knives. If they perform a large number of functions, they most likely will not do any one function exceedingly well. In the case of aerospace vehicle design, performance is the key to success. This is true for both the vehicle and the software used to analyze and develop. Unfortunately, the current state of the software development market is such that a single data structure has not been agreed upon, nor mandated for all vendor applications. For the current time being, most software tools do not communicate well with each other. Although some work is being accomplished, a lack of toolset integration is a reality that will most likely persist for the next ten years.

It is for this reason that integration of multiple "best in class" toolsets is a viable alternative to the idea of an all-in-one environment for systems engineering. The degree to which integration between any two tools can be accomplished varies greatly dependent upon the software data core selected by tool vendor. Data exchange can be accomplished directly, if the tools share a common underlying data structure. But an intermediate translation tool may be necessary in other cases, where tools are based on proprietary, heterogeneous data structures. It would be most desirable for the toolsets to share a standardized data structure that has been agreed upon by all of the tool vendors.

TCSE has been introduced and discussed as the core component to accomplish a CIE. The TCSE tool alone cannot accomplish all of the goals of the CIE. There must be additional software integrated with TCSE to accomplish the various tasks of data sourcing and requirements analysis. It has been shown that the Microsoft Office Productivity toolset is tightly integrated with the TCSE. In addition, there are other tools that are even more tightly integrated than the Microsoft tools. These are complementary tools from Siemens PLM Software, which provide complete interactivity with TCSE, while providing functions that are not found within TCSE. The Siemens suite of complementary tools is displayed in Figure 9.1.

Figure 9.1: Siemens Product Lifecycle Management Software suite of Teamcenter Integrated products. (Teamcenter System Engineering was formerly known as Teamcenter Requirements). [27]

Teamcenter Engineering/Unified

Siemens TCENG is a PDM that also features a database at its core to manage all of the product data and analyses. TCENG was formerly known as the IMAN tool from Unigraphics. TCENG is currently being updated to the new Teamcenter Unified Platform. The new designation is not so much an update to the Teamcenter Engineering functionality, but more the integration of other previously standalone tools into TCENG. Teamcenter Unified would include a much tighter integration of the Teamcenter Systems Engineering (TCSE) tool, which is currently available as standalone software. The Unified platform is the latest milestone in the integration of toolsets by vendors. The paradigm was heavily touted by Dassault Systemes in the late 1990's as a solution to the troublesome work of translating data between diverse tools. For the discussions of this thesis, four Siemens tools will be discussed in terms of their utility to the Teamcenter Systems Engineering Environment. They are: Teamcenter Community, Teamcenter Project, Teamcenter Engineering and Teamcenter Manufacturing.

Teamcenter Community

During the Systems Engineering processes described in previous chapters, there was a need to conduct voting among the IPT to establish the importance ranking of requirements and technologies. This activity lies at the core of the QFD method and creates a basis for multiple quantitative analysis tools. The conduction of this polling is not accommodated in the current functionality of Teamcenter Systems Engineering. The accommodation there is limited to the item creation and downstream use of the importance assignments. There is no dedicated functionality for polling in TCSE.

TCC contains a dedicated functionality for the polling of Integrated Product Team members to determine importance rankings. TCC is a web-based tool that provides project centric workspaces to facilitate distributed IPT collaboration. In this capacity, TCC complements the TCSE tool by providing the collaborative workspace to discuss and ultimately assign priority and importance to the requirement dataset. The two tools can currently be integrated, as shown in Figure 9.2. However, tighter integration is planned for the near future with both TCSE and TCC being incorporated as a fully integrated modules within the Teamcenter Unified.

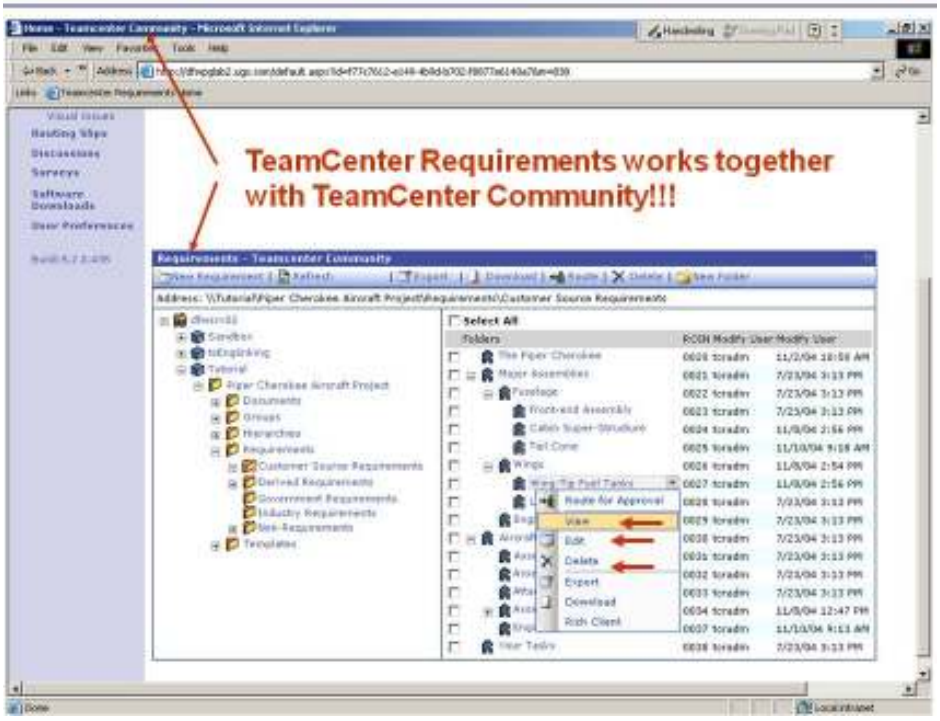


Figure 9.2: Teamcenter Community screen exhibiting the ability to integrate with TCSE Hart, 2009.

There are two benefits of using TCC in conjunction with TSCE that directly reduce the cost and time associated with aerospace vehicle design:

1.) Through the collaborative environment in TCC, it is possible to capture knowledge directly from diverse sources of business intelligence. This would include discussion threads, meeting notes, e-mails among the IPT, website postings, and documents and images related to the engineering of a vehicle design concept. This data is not commonly created in the traditional systems engineering environment. However, the collection and retention of e-mails and meeting notes form the basis of innovation synthesis in the modern engineering department. To achieve a full featured Computer Integrated Environment for systems engineering, it is important to capture the essence of original design concepts, through the integration of TCC collaboration data sets into the systems engineering environment.

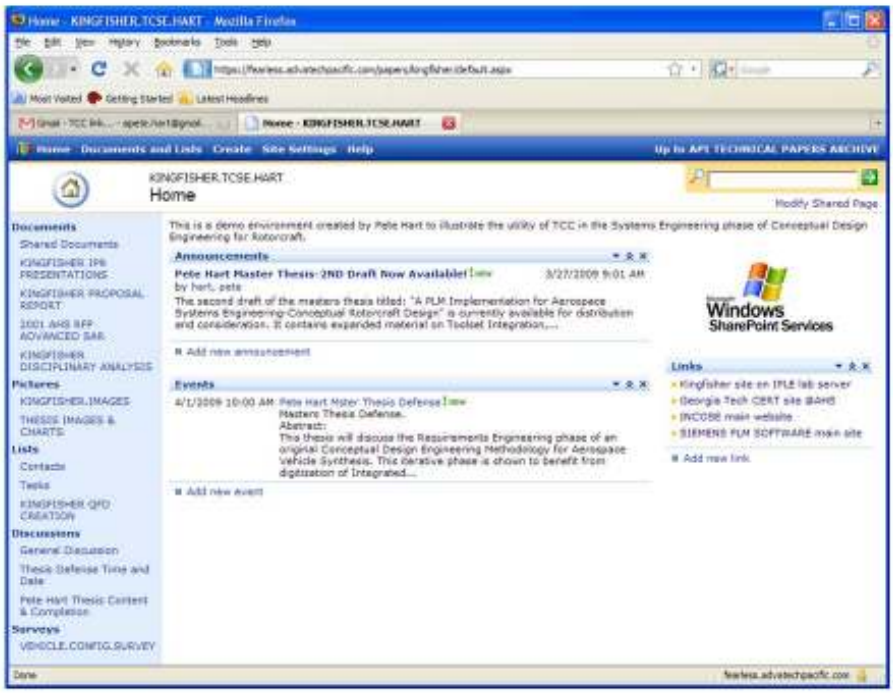


Figure 9.3: Teamcenter Community showing the Main Kingfisher Project Collaboration Site. Hart, 2009.

2.) The IPPD process is predicated on the concept that an integrated product team (IPT) will be collaborating to synthesize a vehicle architecture from an initial set of customer requirements. In the past, it was necessary for all of the members of the IPT to be co-located and physically meet together to complete the system engineering activity. It is no longer necessary to make such impositions on time and location for the team. It is currently possible for geographically dispersed team members to co-locate through online "virtual" meetings, hosted through the internet. Teamcenter Community contains a dedicated functionality to achieve collaborative meetings through the internet using "Application Sharing."

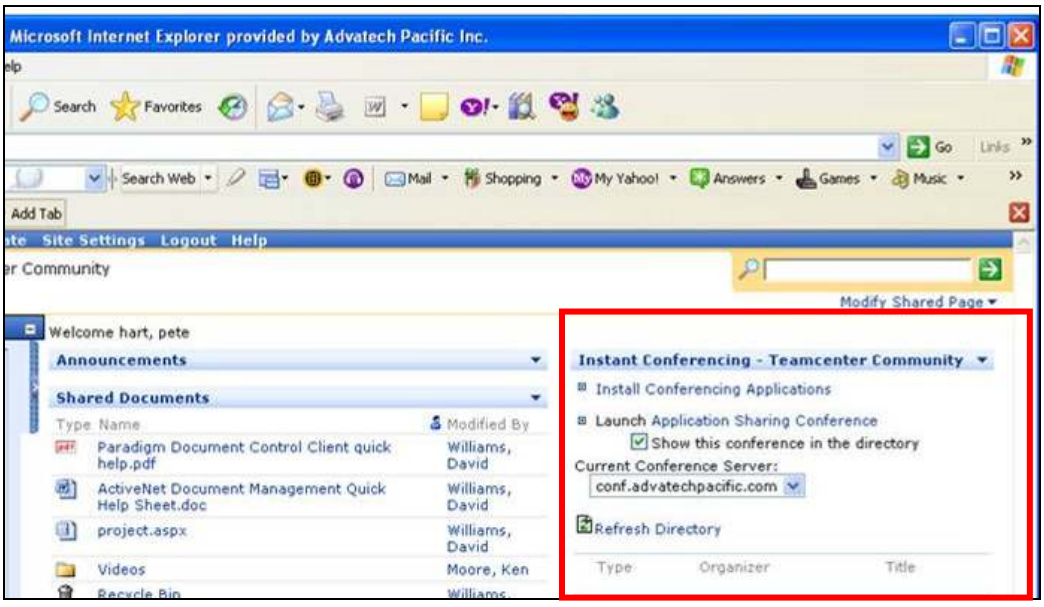


Figure 9.4: Teamcenter Community Application Sharing and Conferencing Utility. The entrance to the application is shown in the lower right hand corner. Hart, 2009.

The application sharing tool within TCC allows a single "host" to begin a virtual meeting. Other team members are given notification of the meeting and invited to join through TCC. Once the IPT members are logged in, it is possible for them to view the live screen content displayed on the computer screen of the "host." This is extremely useful for hosting team meetings, but can also be used to directly reduce the cost and time associated with travel by individuals involved in Intermediate Project Review (IPR). Application sharing provides for interactivity among the virtually assembled team by allowing control assignment of the host computer to any member of the team. In addition, the host may relinquish host control of the meeting to allow content from one of the member computers to be displayed.

The utility of an application sharing session becomes evident when discussing the diversity of software that might be used by the group in conjunction with a team meeting. A best practice associated with a computer integrated environment includes the conduction of virtual meetings, where the team collaborates on a single requirements analysis workspace established within TSCE. The application sharing function is not available in the TCSE tool, and so it is for this reason that the TCC tool is discussed here.

Teamcenter Project

All Engineering projects need to maintain strict adherence to time and budgetary constraints. Project time and cost is traditionally tracked using standardized project management tools in the engineering department. There are two similar tools that will be discussed briefly in terms of integration with the TCSE environment. They are MS Project and the Teamcenter Project standalone tool. These two tools are very similar in their functionality. The only real difference in regards to integration with TCSE is

whether it is done as integrated MS Office module or as an additional Teamcenter module.

Regardless of which tool is employed, the Project software addresses a functionality that is not found in TCSE, namely project administrative management. The project tool provides for timelines to be established, resources defined and allocated, and schedules to be recorded. The software creates a rich environment for tracking the costs associated with the workflow and scheduling activities. A calendar interface provides correlation between workflow and human resources to define capability gaps that could impede project completion. The integration with TCSE would be most evident at this point, due to the fact that workflow assignments are generated in TCSE in direct response to the developed vehicle physical architecture. In this manner, the Project tool provides a sort of administrative bridge between the systems engineering phase and the engineering phase, where the data produced from the workflows to realize the architecture would be routinely accumulated.

Teamcenter Manufacturing

The larger view ability to provide traceability through the lifecycle phases from systems engineering to engineering to manufacturing was discussed early in the current thesis. For completeness, it should be mentioned here that in the near future, the Teamcenter Unified tool will allow for the integration of the manufacturing data manager into a common database used by both the systems engineering data manager and the engineering data manager modules. This will provide for the previously impossible task of integrating vehicle architecture with an EBOM, which is linked to the MBOM. The

standalone manufacturing data manager for Siemens is the Teamcenter Manufacturing (TCMFG) tool (formerly known as Tecnomatix Manufacturing Process Management).

The utility of discussing this capability is to anticipate the "triggers" which initiate changes in the system engineering data, following the formal system engineering phase of development. It is important to leverage the computer integrated environment to support all of the lifecycle phases, downstream of the systems engineering phase. This can be accomplished by creating trace links between TCSE and TCENG data, as well as TCSE and TCMFG in the new Teamcenter Unified.

There are two levels of integration available between the Microsoft Office Productivity tools and TCSE. A choice is made by the user during the Import/Export Function based on the frequency with which the requirement might change within the database.

Discrete Export or Import

The first integration level allows for the discrete export or import of data to a MS Office Tool. The most commonly used tools are MS Office, MS Excel, MS Project, and MS Visio. This option would be used where a tool needs to be populated in a semi-automated manner, without having the need for live updates. This is not a totally automated integration, as might be desired for the types of tools that were discussed in previous chapters regarding the systems engineering visualization and analysis tools.

LIVE Import/Export

The second level of integration available between TCSE and Microsoft Office tools is a totally automated relationship. This level is referred to as the Office LIVE integration. Office LIVE provides for the semi-automated population of the tool, for

example a spreadsheet could be populated easily through the export of several requirement datasets. The Excel LIVE functionality allows for bi-directional automatic updates based on changes made to either the database requirement items or the Excel spreadsheet data. This is an extremely useful function, based on the ability to automatically update Excel-based analysis tools (such as QFD, 7 MaP, and MDO) with rapidly changing vehicle requirements in the database.

This functional magic is not without drawbacks. The ability to automatically change (over write) data is one of the most powerful tools available to any system administration role. The delegation of this functionality to a user in the TCSE database could prove disastrous, unless there is strong best-practices training. The most important realization that must be made is that in an Excel LIVE integration, changes in database items (which should be versioned) will NOT produce a versioned change in the LIVE update of the spreadsheet. The spreadsheet data would simply be over written, without a new version assignment. This is a dangerous situation, as it negates the ability to undo design explorations should they prove to be inconsistent with project goals. The solution to this challenge is to enforce a very strict policy on versioning of the external analysis tools residing in the Microsoft Office software. A restriction of write privilege to a small group of project administrators would also be useful. It is important to specify that versions are created BEFORE changes are made to either the analysis tools or the requirements in the database. This will avoid the probability that data could be lost due to automated data over write.

Regardless of which integration option level is employed, the Microsoft Office tool (the actual Excel or Word file) will not be automatically created in the database. There is a need to use caution in this regard as the MS Office tool may reside in an operating system folder that contains additional non-Live MS Office tools. It would be very easy to confuse which ones are live updates and which ones are not. This would provide for a very disappointing situation when many changes have been made to what was thought to be a discrete MS Excel spreadsheet, only to find that the changes have been automatically over-writing database items.

Microsoft Office (Live) Integration

The integration of the Microsoft Office Productivity tools such as Word, Excel, Visio, and Project with Teamcenter Systems Engineering enables each of the softwares to function more efficiently to reduce time to design. This is accomplished through the deployment of COTS tools that have been purposely integrated through agreement between the vendors (Microsoft and Siemens). The integration of the MS Office tools provides for efficiencies to be realized beyond the functional interdependencies described above.

The MS Office tools are both affordable and common in the existing business office infrastructure of the engineering department.

The reduced cost of the common MS Office productivity tools can directly contribute to overall systems engineering affordability. Word and Excel are commonly deployed in the office computing environment, whether engineering based or not. This commonality of use with other business components offers economy due to the lack of

need for dedicated specialized tool support, as has been the case traditionally with diverse engineering integration software.

The cost reductions afforded by the use of COTS tools are amplified in the context of user training. The familiarity of most academic students with the Microsoft toolset reduces the time and cost of training on these tools. This allows for training to be focused on the higher order functions of the integrated softwares, such as the MS Excel statistical packages, that are value added skills in regards to the system engineering activity. The ease of training on the integrated tools also provides confidence to new and existing engineers who find themselves tasked with providing representation on the Integrated Product Team. These individuals may have been previously tasked with providing support for CAD or Disciplinary engineering analysis tools. Their ascension to the IPT will require that they quickly come up to speed simultaneously on both the systems engineering methodologies and tool suite. The virtual elimination of training on the tool suite can provide additional focus on the implementation of the methodology. Through the application of the methodology prescribed in this thesis, templates and wizards can be created to enhance the rapid success of a newly formed product team.

The integration of the MSOffice productivity tools to provide digital systems engineering analysis of requirements datasets has been demonstrated in detail in previous chapters. The methodology and utility of this capability will be summarized for discussion continuity.

Import

The semi-automated import of data into the TCSE database can dramatically increase the accuracy and decrease the time associated with creating and populating the

systems engineering analysis environment. The import function has maximum effect when used in conjunction with the activities of RFP document decomposition and knowledge re-use through MS Word, Excel Visio, and Project templates created in previous system engineering efforts.

Export

While the ability to automate data importation is a significant contribution to streamlining systems engineering efforts, the ability to export data is even more so. This is due to the need to create a variety of graphical and analytical tools, as well as Report generations for engineering management, intermediate project reviews, and proposals. Time to re-align dataset items and update associated analysis tools is reduced significantly by the use of the LIVE export function.

CHAPTER 10

CONCLUSIONS

A CIE was presented that incorporated a traditional systems engineering analysis method with a dedicated RDM and digitized IPPD tools. The proposed environment shown in Figure M.3 was built upon a COTS database tool, Teamcenter Systems Engineering from Siemens PLM Software. Partial demonstration of the environment was demonstrated on a legacy student design vehicle that resulted from the 18th AHS Professional Society graduate design competition.

The proposed environment was illustrated by example through a step by step discussion of a generic IPPD methodology that newly leverages digital technology. The IPPD methods and tools were analyzed, based on their contribution to the design of an overall complex system, and found to exhibit increased utility from digitization. The benefits were related from three aspects:

1. The ability to reduce the time to define a complex system through a systems engineering process.
2. The ability to increase the quality of complex system designs through automation of repetitive and iterative tasks, and re-dedication of time saved.
3. The ability to reduce the costs associated with design iterations and subsequent design developments through re-use of captured knowledge.

The legacy student design competition example system was used to illustrate portions of the environment. The example was based on the effectiveness of the PLM-

enabled IPPD methodology to analyze a set of rotorcraft vehicle customer requirements in order to identify a functional system architecture. The functional system architecture was further shown to drive the generation of a synthesized set of alternative physical system architectures. The best alternative once identified could be defined as a means for creating a Work Breakdown Structure. In doing so, the system is matured to the point of initiation of a System Design and Definition (SDD) phase kickoff review, based on the entrance criteria of the WBS definition.

The thesis has discussed in detail the Requirements Engineering phase of an original Conceptual Design Engineering Methodology for Aerospace Vehicle Synthesis. The application of PLM technology to the traditional methods and tools was shown to provide a means for substantial savings through integration with a rich variety of best in class office productivity tools. This aspect of the PLM application was further enhanced by the introduction of MS Office Live technology to provide automated updating of related datasets at major design revision intervals.

As such, the proposed environment could serve as an implementation of LEAN principles [47] towards the System Engineering phase of Design Engineering. The application of LEAN principles at this lifecycle phase is non-traditional, but nevertheless effective in the satisfaction of the main tenets of LEAN philosophy:

1. Eliminate Waste (of non value added, manual processes using paper and markers)

2. Maximizing Value (by defining and capturing value in terms of the entire vehicle system, and its associated lifecycle phases)

3. Enabling Flow (reducing non-value added processes, and eliminating re-work)

4. Supporting Pull (enabling the database to respond to the Business Logic Layer to support decision making throughout all lifecycle phases.

5. Achieving Perfection (through metric definition and improvement associated with the system engineering phase processes-specifically the quantifiable reduction in cost due to the reduction in time necessary to perform the IPPD method and related analysis activities.

It can be seen from the thesis discussions that the proposed TCSE PLM tool use could exploit the knowledge generated through the systems engineering phase by directly supporting significant Business Logic Layer processes. Three main business processes have been threaded through the research.

Configuration Management

Configuration Management has been demonstrated in the proposed environment through the versioning of distinct datasets and the imposition of a Product Data Structure within the database. The versioning of requirements, architectures, and work breakdown structures, as well as the individual SE tools allows for effective management of the configuration processes. The ability to create an audit of the TCSE database provides roles based accountability of engineering staff for data production, technical accuracy and validity, performance goals and schedules.

Project Management

Project Management reduction is a derivative benefit of the proposed environment. Through automatically generated e-mail alerts within TCSE, engineering

management can quickly act on work product approvals and commentary. The TCC/TCSE dashboard display shown in Figure 5.6 could be useful to provide the engineering manager with an awareness of real design progress or the lack thereof in order to appraise program progress. The greatest benefit to management of this functionality is to focus attention only on those workflow items that exhibit a red or yellow status. This creates a fundamental gain in management efficiency that may be carried through to all of the downstream lifecycle phases.

Project Archive and Retrieval

The archive and retrieval of vehicle project data in TCSE constitutes a general knowledge management library populated by the system engineering data. The MS Office integration with TCSE allows for database capture of a total project including IPPD analysis processes and component datasets, and all intermediate and final proposal documents. The utility of this capability could be seen as providing the necessary Systems Engineering data support in the following three areas:

1) Manufacturing/Use/MRO engineering phases for the Kingfisher vehicle in later years of possible development as a commercial vehicle.

2) Derivative design developments that utilize the captured data as a template (accommodating re-sizing, or mission alterations).

3) Single Technology Extraction from a legacy design (for example, the advanced flight control featured on the Kingfisher legacy vehicle design).

The PLM-enabled System Engineering process has been shown to provide the ability to reduce risk for complex systems development by providing positive compliance

with customer generated requirements. Risks are also associated with the implementation of cutting edge technologies in vehicle systems. The proposed environment has been shown to provide the ability to create traceability of requirements to satisfactory engineering characteristics and the resulting product architectures through the use of QFD and Trace Links. This helps to minimize the opportunity for technology infeasibility in the design. The elimination of these issues in the development of complex systems promotes "the right technology applied correctly." When done efficiently, this can make the difference in the vehicle system overall success by being first to market.

In conclusion, the deployment of the proposed PLM-enabled System Engineering methodology for the conceptual design engineering of rotorcraft vehicles could save time and money. An example of the amount of money saved can be conservatively calculated through the following calculations:

Assuming an engineering team member salary of $80.00/hour and an IPT membership of 12 (including management), working for 20 weeks to develop the vehicle design engineering proposal, the estimated time savings is 3 weeks. This is gained through the re-use of a previously created template for the System Engineering Requirements data manager, including trace links associated with the IPPD toolset, and all supporting documents.

$80/hour x 40 hours/week x 3 weeks saved x 12 team = $ 115,200.00 saved.

This is an example estimation of the time and cost savings that may be conservatively realized through the implementation of a PLM-enabled Collaborative

Engineering Environment dedicated towards the conduction of the System Engineering phase of Conceptual Design. The estimated cost savings could be significant. However, the time savings cannot be purchased with any amount of money. It is for this reason that the proposed environment gains amplified value in the affordance of time re-dedication to the tasks of TRL value elevation towards the proposal of superior vehicle designs.

CHAPTER 11

FUTURE WORK

While the comprehensive investigation of the preceding thesis material is accomplished from both a Lifecycle perspective and a Systems Engineering perspective, there are many opportunities for the continuation of this research on a variety of levels. An educated extrapolation from the presented thesis data is produced in this chapter. It is intended to provide guidance and suggestion on future research areas that will provide industrial benefit and personal growth. The areas of future investigation are arranged in an order, progressively radiating downstream in the lifecycle phases, including an over arching body of work on the entire vehicle lifecycle.

Integration of Probabilistic Methods: Integration with MDO Tools

The most obvious future work to be accomplished is the completion and demonstration of the integration of the probabilistic methods discussed in Kirby [xx]. These methods have gained widespread popularity in the DoD and aerospace industries since the 1980's. It is recommended that these tools be integrated into the Teamcenter Systems Engineering tool, in order to provide Versioning and data archive functionality that is badly needed by the engineering managers working with these tools. TCSE and the Computer Integrated Environment proposed in this thesis may seem overly simplistic in comparison to the probabilistic methods. Regardless, these complex tools are reliant on the Customer Requirements and need to be integrated into the Project management database so that they may be intimate with the proposed example IPPD toolset. This is a

modern goal for both industry and academia that can now be met through the accomplishment of additional work in the newly available environment.

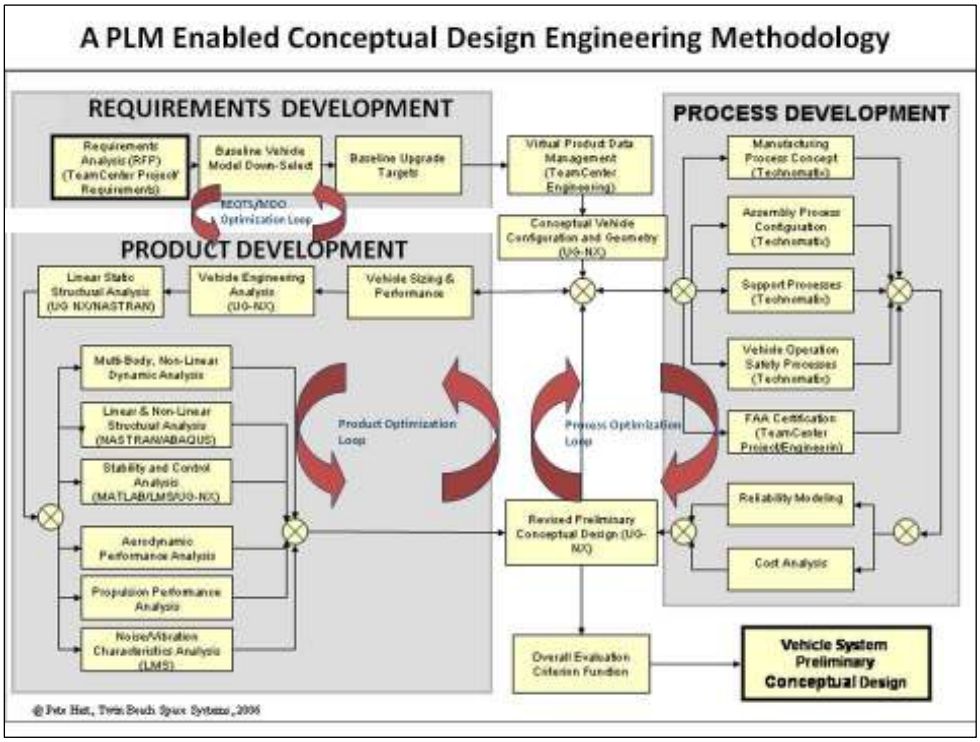


Figure 11.1: An original PLM enable Rotorcraft Design Engineering Methodology, featuring Optimization Analysis at the Engineering Phase. Hart, 2009.

In this thesis, the CIE was illustrated through example as a repository, workplace, and library for the conceptual engineering design phase data of an overall rotorcraft vehicle design. The subsystems of the vehicle should serve as a fertile area to conduct further investigations into the technology employment from a variety of perspectives including functionality, geometric region, and discipline. This can only help to strengthen the knowledge capture capability of the CIE by creating depth of detail below the first order vehicle system architecture. It is expected that Robust Design Simulation employed along with probabilistic methods will greatly enable this task.

The future work associated with increasing the depth of the IPPD methodology datasets can prove to be a significant asset to corporations based on the ability to reverse engineer successful legacy vehicle systems. The historical documentation of fielded vehicle systems can be a rich source of engineering business logic, which can be leveraged towards the design of new vehicle systems. With the advent of the $2000 automobile from Tata Motors, the aerospace vehicle market will be under heavy pressure to produce similar vehicles for greatly reduced cost. Much like Tata borrowed and improved on the automotive knowledge of Detroit, future vehicle manufacturing operations will be pressed to accomplish a similar task. One method of successfully achieving these types of performance in the marketplace is through the effective reverse engineering of legacy vehicle systems in the context of the system engineering data manager. TCSE could be used to distill re-useable requirements from legacy subsystems, possibly resulting in affordable designs which meet or exceed performance standards.

Teamcenter Systems Engineering was examined and found to be of unique utility in the creation, hosting, and integration of the requirements analysis datasets. The tool that was presented in this thesis is the version 2007 of TCSE that is commercially available. It is outfitted with all of the functionalities that have been described. The main area of improvement that can be accomplished in the future with TCSE is the integration with the other lifecycle data managers. This would result in a single database architecture, reducing the information technology management load. An example of this to-be system is shown in Figure 11.2. Of particular importance in this figure, the feedback loops are shown arching back to the Systems Engineering Data Manager. Because the product configuration data is derived from the requirements at this phase, it

is a best practice that challenges encountered downstream would be related back to the original systems engineering dataset for requirement augmentation or replacement.

The use of these feedback loops is triggered by predictable events at the lifecycle phases. These could include such events as supply chain disruption, commodity value shifts, cultural re-alignment, stricter regulatory processes and inevitable technology obsolescence. Experience over time may provide the ability to identify trends relating to the inclusion of appropriate additional requirements in the original systems engineering phase. In the future, it is anticipated that the integrated database architecture will provide for the conduction of off-line simulations of real and imagined triggering events programmatically. This would be done to ensure product system success, regardless of lifecycle triggers and extra-enterprise influences.

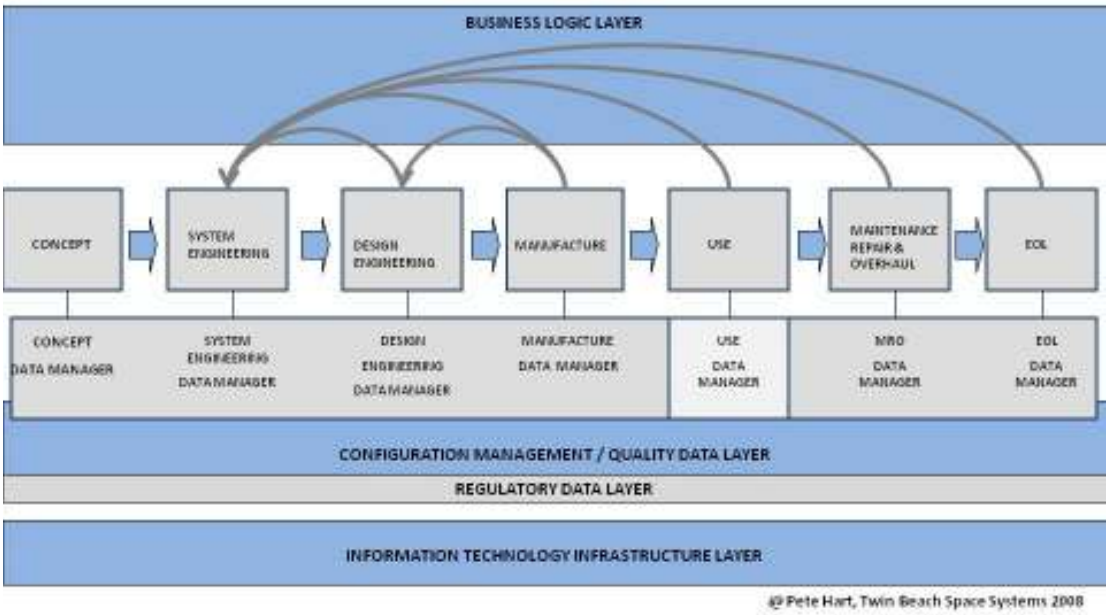


Figure 11.2: The to-be lifecycle from the JNJ material on Allowable Configuration showing the integrated lifecycle phase databases, and feedback loops to the requirements engineering processes. Hart, 2009.

It is important to note that the to-be Computer Integrated Architecture depicted incorporates all of the diverse lifecycle phase data managers into a single database. This

would eliminate the need for data translation and transport at any point in time. It would also facilitate truly integrated product and process design by actually integrating the product and process data in a single location. This may seem like the type of activity that will be achieved in another man's lifetime. However, the fact is that this technology currently exists and is advancing out of the development phase into the deployment.

Teamcenter Unified Architecture

A new all-in-one database architecture is being released in late 2009 which will accomplish the integration of the formerly diverse data managers. This has not been previously available from any single vendor in the past. The Teamcenter Unified Architecture from Siemens PLM Software will combine the functionality of TCSE into the same database (Oracle…) as the Product Data Manager and the Manufacturing Process Data Manager. The integration of these three key database elements will greatly aid in the design engineering activity of new vehicles. However, the greatest increase in overall vehicle system lifecycle affordability will be realized through the integration of the Requirements and MRO lifecycle phase data managers. This is due to the fact that the MRO activities are repeated many times during the entire vehicle lifespan. Savings incurred during the re-design of flight vehicles to meet evolving needs of MRO processes are recurring. The ROI on the ability to access the legacy requirements and engineering databases to rapidly realize as yet unknown MRO triggered vehicle and sub system re-designs will be significant. In terms of overall savings, the cost benefit to MRO activities is estimated to be many multiple times the cost savings afforded by an integrated requirements/engineering/manufacturing data environment. This is a significant benefit

that is generally invisible to the Integrated Product Team engaged in Vehicle Design Engineering.

Lifecycle Quality Assurance Activity	Frequency During Lifecycle
Requirements Engineering	1
Design/Engineering	1
Manufacturing/Assembly	1
MRO/Device Service	10-20

Table 11.1: Frequency of Major Activities in a Vehicle Lifecycle. Hart, 2009.

The utility of this type of integrated database arrangement can be seen in a single vehicle system exhibiting a common challenge. The NASA Space Transportation System (STS) was originally envisioned as an extremely affordable alternative to disposable rocket technology. However, based on the high costs of MRO and the inability to reduce turnaround time to engineering-defined values, the Space Shuttle program has been cancelled. While newly considered risk assessments played a major role in this decision, the most prominent reason for system retirement was MRO time and cost. It is envisioned by the author that in the future, the design and engineering for MRO will be required by contracting authorities to play a much larger role in the upfront Systems Engineering processes. The availability of the proposed Requirements Data Manager and an integrated MRO database will be of great utility in satisfying that need.

Risk, Cost, TRL, Reliability Component Rating

One of the primary reasons for deploying a Computer Integrated Environment is to be able to recall data associated with a design and operate upon it. Aerospace design engineers by nature and training are keen to identify technological solutions which

provide high performance in vehicle systems. However, most often, vehicle systems are not ended due to the lack of technical merit, but rather a lack of economic viability. Cost has become one of the key drivers of system engineering success and failure. The deployment of a digitized systems engineering methodology not only saves time and costs, but can also track those same costs, as true as any accountant.

Database Item Creation

The tracking of costs can be greatly enhanced through the assignment of appropriate costing data at the component levels of system architectures as early as the requirements engineering phase of design. This is accomplished through the creation of a dedicated field in the TCSE database that can be attributed to the routine database item types, such as the functional architecture building blocks. The maintenance of the allocated cost data throughout the lifecycle databases eliminates much of the guess work that is involved with trying to achieve and maintain accurate and realistic cost limitations. It is for these reasons that a variety of parameters are proposed to be identified in the TCSE database, so that they may provide decision making support in multiple dimensions, in excess of the system configuration and performance engineering so familiar to aerospace engineers. This methodology is suggested to be employed with a number of important parameters such as Cost, Weight, Risk, Technology Readiness Level, and System Component Reliability Rating. These parameters can each be audited at the appropriate design review intervals through the functionality of the search function or the simple export of the system functional architecture to an Excel spreadsheet where a variety of traditional and customized accounting methods may be employed. This is a

non-standard utilization of a database environment created primarily for systems engineering, but an important and desirable utilization nonetheless.

Decision Management Strategies

Once a CIE is achieved to provide decision making support, the only remaining task is to identify which decisions to support. The deployment of DoD-mandated digital systems engineering environments will undoubtedly reveal opportunities to support a far wider spectrum of decisions than is currently possible. This is indicated in Figure 11.2 by the intersection of the feedback loops through the Business Logic Layer. The graphical depiction reveals that cost savings decisions made in downstream lifecycle phases can be directly supported through the system engineering methodology proposed.

Environmental Compliance

An example of the enhanced decision making support enabled by the to-be CIE depicted in Figure 80 is the adjustment by industry to newly emerging Environmental Regulations. New mandatory compliance with strict environmental regulations for both product materials and the processes used to produce them will have a profound effect on the aerospace vehicle design community over the near term. One solution for compliance is the attachment of required material content datasets to the system components on a part by part basis within the lifecycle phase databases. The integration of the requirements and engineering databases in the short term will allow forward traceability for material utilizations to be determined and attributed to affected requirements. Operating in this way, the requirements database items can be evaluated to certify compliance and eliminate non-compliant system components and processes at the requirements phase of

new or mandated re-design product developments. This is currently and will continue to be a major design influence for the next decade.

The utility of programming to expand decision making support for contexts which span a larger space than is accommodated within the Systems Engineering phase of vehicle development.

APPENDIX A

ORIGINAL TEXT OF THE 2001 AHS RFP

2001 Request For Proposal (RFP)

For

Advanced Rotor Control Concepts

18th Annual Student Design Competition

For

Undergraduate And Graduate Students

Sponsored by: BOEING

And

AHS International The Vertical Flight Society

End page one

Table of Contents

Section 1.0 Basic Proposal Information	2
I. Rules	2
II. Schedule And Activity Sequences;	4
III. Proposal Requirements	5
Section 2.0 Design Objectives and Requirements	7
I. Mission Needs	7
II. Project Objectives	7
III. Requirements and Constraints	9
1.0 General Requirements	9
2.0 Fleet size and Mission Profile Requirements	9
3.0 System Capabilities Required	10
4.0 Data Package	12
IV. Proposal Data Package Requirements	13

End page two

Section 1.0 Basic Proposal Information

I. Rules

1. Competition categories include:

Graduate For-Credit (as a part of a Design Course or Independent Study)

Undergraduate For-Credit (as a part of a Design Course or Independent Study)

Not-For-Credit (not a part of a Design Course or Independent Study)

2. Schools are encouraged to form project teams. The number of students on each team may be determined by the· school.

3. All undergraduate and graduate students may participate in this competition. For submittals in the For-Credit categories, the classification of a team is determined by the highest education level of any member of the team. Part time students may participate at the appropriate graduate or undergraduate level. In the Not-For-Credit category, both graduate and undergraduate students may participate.

4. Only one design proposal may be submitted by each student or team; however, any number of design proposals are permitted from a university or college.

5. The competition consists of a written Proposal Outline, a written Final Proposal, and an oral presentation (for fmalists selected after judging of the written proposals). As in industry, after review of the Proposal Outline the AHS may provide each team with requests for clarification specific to its Outline. Responses to the requests could be submitted separately, or could be included in the Final Proposal. Final presentations will be given at the AHS Mideast Region Specialist Meeting on Crew stations and Flight Controls in Philadelphia in October, 2001, for which travel stipends of approximately $1000 will be made available.

6. Documents must be submitted to the AHS in digital format readable using Microsoft Word 97, PC format. (Requests for exceptions will be considered in advance). All documents submitted shall be double-spaced with a font of at least 10 point. All material must be legible.

The written proposal outline will be due on March 30, 2001. It shall be limited to no more than 20 pages (including all graphs, drawings and photographs).

The Final Proposal will be due June 22,2001. It shall be limited to no more than 75 pages (including all graphs, drawings, photographs, and appendices). Up to 8 of the 75 pages may be larger than 8~"x 11", such as fold-outs up to a maximum size of 11 "x22".

The Final Proposal document must include a self-contained Executive Summary, limited to no more than 7 pages including all graphics. This summary is not to be considered a part of the 75 page limit.

End page three

7. Presentations must be submitted to the AHS, in advance of the Specialists Meeting, in digital format readable using Microsoft PowerPoint 97, PC format. (Requests for exceptions will be considered in advance).

8. For all submittals, an inside cover page must include the printed name, educational level and signature of each student who participated. Submittals must be the work of the students, but guidance may come from Faculty Advisor(s), and must be acknowledged on this signature page. Design projects for which any student receives academic credit must be identified as such on this signature page, and will be considered in one of the For-Credit categories.

9. All Submittals are to be provided to:

Kim Smith, Deputy Director American Helicopter Society (AHS)

217 N . Washington Street, Alexandria, Virginia 22314

Tel. # (703) 684-6777

Fax # (703) 739-9279

Email AHS703@aol.com

10. The Awards shall be:

Graduate For-Credit Category	Undergraduate For-Credit Category
1 st Place $750	1 st Place $750
2nd Place $250	2nd Place $250

Not-For-Credit Category

1 st Place $750

2nd Place $250

11. Certificates will be presented to each member of the winning teams, and to their Faculty Advisors for display at their school.

12. A representative of each winning team in the Graduate and Undergraduate Categories will be expected to present a technical summary of their air vehicle design at the AHS Annual Forum 58, in May of 2002. A stipend of $1000 will be provided for each first place team in the Graduate and Undergraduate category to heIr defray the costs of attending the Forum. The first place winners or members of the winning teams will receive complimentary registration to the 2002 AHS Annual Forum.

13. If any student or design team withdraws their project from the competition, the student or team leader must notify the AHS National Headquarters Office immediately in writing.

End page four

II. Schedule & Activity Sequences

Scheduled milestones and deadline dates for submission of the proposal and related material are as follows:

A. AHS Issue of Request for Proposal (RFP) August 21, 2000

B. Teams Submit Requests for Information/Clarification by February 15, 2001

C. Teams Submit Proposal Outline due to AHS by March 30, 2001

D. AHS Issue Responses to Questions & Requests for Clarifications by May 15,2001

E. Teams Submit Final Proposals by June 22, 2001

F. AHS Notifies Finalists August 1,2001

G. Teams Submit Presentation Material to AHS September 8, 2001

H. Teams Present at AHS Specialists Meeting (philadelphia) October, 2001

I. AHS Announces Winners December 1,2001

J. Winners Present Designs at AHS Forum 58 May, 2002

All questions by teams put forward to the AHS before submittal of the Proposal Outline will be distributed with answers to all participating teams. Any Questions or Requests for Clarifications from the judges after review of a team's Proposal Outlines will not be provided to other teams.

All submittals must be postmarked on or before the dates specified in Items C, E and G.

End page five

III. Proposal Requirements

The content of the proposal needs to communicate a description of the design concepts and the associated performance criteria (or metrics), to substantiate the assumptions and data used and the resulting predicted performance, weight, and cost. The following should be used as guidance while developing a response to the Request For Proposal (RFP).

1. Demonstrate a thorough understanding of the RFP requirements.

2. Describe the proposed technical approach that complies with the requirements specified in the RFP. Technical justification for the selection of materials and technologies is expected. Clarity and completeness of the technical approach will be a primary factor in evaluation of the proposals

3. Identify and discuss critical technical problem areas in detail. Descriptions, method of attack, system analysis, sketches, drawings, and discussions of new techniques should be presented in sufficient detail to assist in the engineering evaluation of the submitted proposal. Exceptions to RFP technical requirements must be identified and justified.

4. Describe the results of tradeoff studies performed to arrive at the fmal design. Include a description of each trade and the list of assumptions. Provide a brief description of the tools and methods used to develop the design.

5. The data package which must be provided in the proposal is described in Section 2.0, IV.

End page six

IV. Basis For Judging (Weighting Factors)

1. Technical Content (40 points)

• Design meets RFP technical requirements

• Assumptions clearly stated and logical

• Major technical issues considered

• Appropriate trade studies performed to direct/support the design process

• Well balanced and appropriate substantiation of complete system

• Technical drawings accurately describe the complete aircraft and its subsystems

2. Organization & Presentation (15 points)

• Self contained Executive Summary which contains all pertinent information

and makes a compelling case for why the proposal should win.

• Introduction clearly describes the major features of the proposed aircraft

• All pertinent and required information included and easy to find

• Continuity of topics

• Figures, graphs and tables are uncluttered and easy to read and understand

• All previous relevant work cited

• Overall neatness of report

3. Originality (20 points)

• Treatment of problem shows imagination

• Concepts show originality

• Unique vehicle attributes and subsystem integration show innovative thinking

• Vehicle aesthetics

4. Application & Feasibility (25 points)

• Current and advanced technology levels used are justified and substantiated.

• Particular emphasis should be directed at identification of critical technical

problem areas.

• How affordability considerations influenced the design process.

• How reliability and maintainability features influenced the design process.

• Manufacturing methods and materials are considered in the design process.

• Proposal shows an appreciation of how the vehicle will be used by the operator.

• Consideration of additional applications and capabilities other than those in the RFP.

End page seven

Section 2.0 Design Objectives and Requirements

I. Program Objectives

The topic for this project is the development of a VTOL platform with an innovative method of controlling the cyclic pitch of rotor blades. Methods that do not depend upon the use of traditional swashplate mechanisms are sought. Traditional tiltrotor and helicopter rotors use a swashplate mechanism to transfer rotor control inputs from the fixed frame of reference to the rotating frame of reference. This mechanism has proved to be reliable over time, however, it presents several limitations to the designer in that blade control inputs are limited by the physical constraints of the swashplate. Attempts have been made to develop alternative means of rotor blade control without conspicuous success. It is believed that the latest developments in materials and controls technology and advanced actuators, especially smart metal technologies, may offer a new opportunity to investigate advanced rotor blade control methods.

II. Project Objectives

The objective of this design competition is to develop the conceptual design of a modem civil search and rescue (SAR) VTOL rotorcraft. The vehicle must incorporate new and innovative methods of controlling the pitch of rotor blades. A balanced approach to risk is desired to optimize investment and qualification/certification costs.

The primary challenge is to produce the design for an advanced, high performance, rotor control mechanization that is affordable and capable of being developed to meet flight safety qualification and all other airworthiness requirements. The design is required to address the following topics: design of reliable actuation technologies and methods that are capable of providing the necessary control forces; design of reliable and accurate means of measuring rotor states for all degrees of freedom, including flapping, feathering, and lead-lag motions; and design of reliable methods of transitioning all required information across the boundary between the fixed and rotating frames of reference, including the required sources of actuator motive power. Emphasis must be placed on developing a safe and reliable mechanization, such that analysis of failure causes and effects must be considered in the design process. Provide actuator power required, failure modes of the chosen technology/design, maturity of the technology (present and future), and future research required. This portion of the effort is worth 40% of the total points available.

The proposals shall also provide design definition and estimates of performance attributes for three separate areas; the aircraft configuration design and sizing, the crew station definition, and the flight control system to support the innovative rotor control system. Each of the areas is worth 20% of the total points available.

1. Aircraft Configuration Design, Mission Specification and Sizing Groundrules

 End page eight

The aircraft is required for Search-and Rescue (SAR) mission in adverse weather conditions. The objective of this effort is to perform trade study evaluations of vertical take-off & landing aircraft (helicopter, tiltrotor, other) for a representative search and rescue mission. The mission specification is provided in Section 2.0. Assess the benefits and drawbacks of utilizing a "swashplateless" rotor.

2. Crew Station

A key aspect of any aircraft design is it's interface with the crew. The objective of this design effort is to design a cockpit I crew station that enables the crew to address the unique requirements of the SAR mission. The design should address both the cockpit and cabin crew stations.

The cockpit crew interface shall include interfaces to enhance the situational awareness of the crew. The interface should highlight unique features of your design and I or unique interfaces required to support the SAR mission in adverse weather. Drawings must be included, as well as a description of the interfaces. Human Engineering principals and practices shall be used in the design process. Unique features of your display and inceptor design should be highlighted. Special attention should be paid to adding capability which reduces pilot workload without adding significant cost to the design.

The cabin crew station shall include interfaces necessary for the para-rescuers to perform their mission and keep the aircrew informed of status. The interface should highlight unique features of your design and lor unique interfaces required to support the SAR mission. Drawings should be included, as well as a description of the interfaces.

3. Flight Control System

For mechanical controls, a description of the kinematics, inceptor forces and antiicontrol jam design must be included. A list of flight control parts must be identified. The design criteria for loads, dynamic performance and life must be addressed. Qualification methods for the FCS shall be described, including identification and justification of pass/fail criteria.

For electronic flight control components, a description of the architecture of the flight control system (PCS) and its theory of operation must be presented. A description of the flight control computers, sensors, inceptors and actuators shall be presented.

For software used, the proposal shall include a description of software development, including development processes, software architecture, special sampling requirements, and discussion of failure management and fault isolation.

The FCS should have a reliability of less than one failure in 10^7 flight hours. Redundancy to meet this requirement shall be described and justified by analysis.

End page nine

III. Requirements and Constraints

1.0 General Requirements

The market requires a dual-piloted, vertical takeoff and landing (VTOL) rotorcraft. The aircraft shall incorporate high value technologies in airframe, propulsion, and aircraft human factors engineering. The new system will provide dramatic improvements in performance, and system commonality.

The aircraft must provide search and rescue service in IFR conditions at a range of 300 nm. The mission includes fly-out, loiter, perform a rescue of 2 people and return to base.

It is anticipated that launch of the configuration will lead to delivery of the frrst aircraft in the year 2015. An average production rate of four aircraft per month should be used.

2.0 Mission Profile Requirements

Perform sizing trade studies for a "range mission" and an "endurance mission" as given below. Choose a suitable configuration that meets each of these requirements.

Range Mission·

basic requirement is 600 nm range at an altitude of 500 ft @ ISA +/- 15 deg. C conditions.

Endurance Mission -

basic requirement is 5 hrs at no speeds no less than 60 knots, not greater than 120 knots @ 500 ft P A, in ISA conditions.

Final evaluation mission·

This is the primary mission for the design competition. It is meant to be loosely based upon the mission flown in the novel The Perfect Storm, by Sebastian Junger (see http://www.aperfectstorm.com/#).

Segment	Profile (all at normal SAR weight)
A	10 min. warmup @ idle (25% MCP) @ 0 ft, ISA day
B	Take-off and climb at max. climb rate to 500 ft PA, at max. fuel
C	Cruise at 99% best range speed for 300 nm (refueling optional), (appropriate or max fuel)
D	loiter in hover for 15 minutes on station in 30 knot cross wind with 50% gusts (at 60% fuel) while evacuating 2 from a sinking boat.
E	Return cruise for 300 nm (headwind = 60 knots 0-10K, 40 knots 10K-15K) (appropriate or 50% fuel· refueling at altitudes above IOKft only)
F	Land with 15 min. IFR reserve @ 500 ft PA

End of page

Fixed Useful Load Evaluations-

The "normal" SAR crew will consist of 4 crew @ 200 lb each; 2 flight crew and 2 pararescuers.

Tasks 2 & 3 will define the requirements for the remainder of flXed useful load.

Fixed useful load should be itemized and specifications must be provided for:

a) communications, for the aircraft and crew

b) mission system equipment including navigation, weather aids, night vision, FLIR

c) rescue/survival gear for aircraft, crew and passengers

d) refueling kits, if it required to meet the mission requirements

(this is part of the configuration trade)

e) medicallEMS equipment

f) heating/de-ice systems and sensors for the aircraft

g) crew, crew safety and crew's personal equipment

An estimate of the cost, weight and drag implications for each of the equipment listed above must be provided. Costs should consider both recurring cost (equipment, installation, maintenance) and non-recurring cost (qualification testing, design/development, redundancy/integration provisions). Weight and drag should consider internal vs. external requirements (fasteners, holes, braces).

Notes:

> Fuel type - assume NATO F40 (JP4), 6.693IbIUS-gal. Or alternate

> De-ice equipment must be on in known icing conditions per Air Weather Service Manual (AWSM 105-39),5 January 1969.

3.0 System Capabilities Required

• The aircraft must also be capable of power-off glide/autorotation to a survivable emergency landing.

• Manual rotor blade folding is desired to minimize hangar requirements.

• Cabin storage capacity is 1 patient, 2 crew and equipment (2ft D x 6ft W x 4ft H).

• Authorized flight envelope must be consistent with appropriatc. F ARs for the design gross weight and should be capable of a transient turn capability (loss of airspeed and/or altitude allowed) at cruise speed equal to a standard rate turn (Minimum capability = 30° bank turn).

• For maximum takeoff and landing safety, the aircraft must provide a one engine inoperative (OE!), hover-out-of-ground-effect (HOGE) capability at 60% fuel and full

payload capacity using no more than Emergency power at sea level, ISA+20°C ambient conditions. For scaleable or developmental engines, consider emergency power to be 25% above the takeoff power rating.

• A flight crew of four is required, with side-by-side cockpit (pilot and copilot) seating, and cabin seating for a flight surgeon and a flight nurse.

• No cabin pressurization is required.

• The aircraft must be capable of reliable unassisted self-starting.

• The design must include the mission equipment (navigation, sensors, communication gear, etc.) required to perform the SAR mission in adverse weather conditions and night operations.

• The aircraft must be designed to facilitate basic aircraft maintenance. The design must facilitate access for inspection and rapid repair/replacement of all aircraft components (engines, transmission(s), avionics, hydraulic/electricallfueVcooling systems, flight controls, etc.).

• The design must consider the elements of good crashworthiness design per FAR Part 29, including:

• Landing gear struts that do not penetrate the cabin area

• High mass items (engine and transmissions) that have adequate crash protection to prevent entry into the cabin areas

• Crashworthy fuel tanks,

• Adequate seat stroke (at least 8 inches).

• Designs for low noise are required to minimize external noise (community impact) and internal noise. Since rotor advancing tip Mach number is a significant noise source, it is suggested that advancing tip Mach number be limited to 0.87 for cruise conditions. In addition, 1 % of the design takeoff gross weight should be allocated for internal noise reduction treatments.

• Emerging turboshaft engine technology levels should be assumed, including llIPTET technologies. Other engine types may use similar factors on SFC and weight. If data are not available, use the scaleable turboshaft data provided in the data package.

End of page

4.0 Data Package

These data are provided as reliable estimates but should be afforded some level of scrutiny in any rigorous analysis. Changes are acceptable with supporting technical data.

Weights

Fixed Equipment Weights (as required)

Avionics 650 lb

Payload Characteristics

Crew 200lb

Patient 190 lb

Scaleable State-of-the-art Engine Characteristics

Scaleable turboshaft engine SFC characteristics are provided here. Data are static. uninstalled. If existing engine data are used. assume a 25% reduction in SFC and a 40% improvement in power to weight ratios. representing IPTET improvements.

Engine	Rating Ratios	Duration	SFC/delta*theta^0.5 (lblhrlhp)
1.250	(OEI. Emergency)	30 sec.	0.302
1.000	(Takeoff or MAX)	2min	0.305
0.924	(IRP)	30min	0.309
0.791	(Cruise or MCP)	Continuous	0.328
0.5	(partial power)		0.400
0.2	(Idle)		1.000

Engine Weight.lb = 160 + 0.05539 * (Design SHP)

Engine Diameter. ft = 0.017 * (Design SHP)o.s

Fuel Density.lb/gal = 6.75 (Jet A)

Ram power increase with speed may be assumed to follow:

[deltaSHP/(SHP @ V=O)] = 0.00016 - 4.63x1O^-5(V/theta^0.5) + 2.32xl0^-6 (V/theta^0.5)^2

Where, SHP is in Hp. V is in knots and theta is the absolute temperature ratio, (459.7+T°F)/518.7°R.

IV. Proposal Data Package Requirements

The design proposed must meet the above stated objectives, requirements, and constraints. The following data shall be furnished:

I. Justification for the air vehicle design submitted. Include discussion of the tradeoff studies (describe analysis methods and tools) that were performed to arrive at the proposed design. Present the performance, weight, handling qualities, reliability and maintainability, manufacturing materials and techniques, and cost criteria by which the final designs were chosen. Include the sizing trade study results to show how the pertinent vehicle configuration parameters were chosen, such as rotor system size, type of anti-torque system, wing span and aspect ratio, engine size, etc. If multiple vehicle types were initially considered, describe the rationale for the vehicle type selection.

2. A set of drawings which depict the air vehicle and includes, but is not limited to:

• Fully dimensioned three view drawings

• A dimensioned system integration/general arrangement(inboard profile) which shows the location and arrangement of the major subsystems.

3. The structural design, including materials, must be described. Weight breakdowns for the vehicles shall be provided in MIL-STD-1374, Part I format. Weight and balance charts must be provided with the weight statement. The center of gravity and it's allowable travel shall be indicated on the three-view drawings, along with tip-over and tip-back angles.

4. Describe the analysis methods and the results of the flight performance (including rotor performance), stability and control, and handling qualities evaluations of the design. A description of the flight control system shall be provided.

5. A description of the engine installation and drive system shall be provided, along with tables or graphs of performance (installed engine power and/or thrust available as appropriate for the aircraft concept, drag/download analyses, fuel flow, etc.). If the engines selected are not existing engines, provide a discussion of the technology involved and the current state of development of such engines. Data tables or charts must be provided which specifically indicate the proposed aircraft designs will meet the flight performance and mission requirements.

6. If the proposed aircraft concept reqUires conversion between rotor and wing borne flight, a description of the means to provide this shall be provided. Also, the flight performance, stability and control, and handling qualities aspects of conversion shall be addressed and described.

7. A description and associated drawings of both the cockpit and cabin crew areas.

End page

8. A description of the mission systems (avionics) suite. Existing equipment (offshelf) as well as equipment with new/unique requirements shall be described.

9. Reliability and maintainability aspects of the air vehicle design shall be addressed. Configuration and other features such as easy access to avionics, quick engine removal, minimum of special tool, unique designs, etc.

10. Acquisition and operating cost of the air vehicles shall be addressed, including manufacturing cost and direct and indirect operation costs. Assume a production run of 300 aircraft and a use of 2000 flight hours per aircraft per year. Include a description of the methods and data used for cost analysis.

11. Manufacturing approaches and risks for non-traditional hardware designs shall be addressed. Identify specific material handling, manufacturing tolerance or other unique concerns introduced.

Note: Any additional data or analysis which can be provided to add to your design's credibility within the page count constraint is welcome.

End page

APPENDIX B

2001 Kingfisher Proposal Report, Georgia Tech Aerospace Engineering

18th Annual Student Design Competition
Advanced Rotor Control Concepts
Final Proposal

For Graduate Student Design Competition Sponsored by Boeing and The American Helicopter Society International

The *Kingfisher*
(The Georgia Tech Search and Rescue Vehicle)

Submitted by the Georgia Institute of Technology
Graduate Student Design Team

22 June 2001

Signature Page

Georgia Tech Graduate Student Design Team

Joerg S. Dittrich	Michael D. McKay
Dong-Ho Seo	John O. Nugent
Peter B. Hart	Luke J. Preisner
Jong-Hyuk Lee	Joseph R. Taylor

Dr. Daniel P. Schrage
Project Faculty Advisor

Academic Credit

All members of this design team received academic credit for all work done on this proposal. This proposal was the capstone project for AE6332, Rotorcraft Design II, a four credit-hour graduate aerospace engineering course offered by Georgia Tech and instructed by Dr. Daniel P. Schrage. All team members have completed one year of graduate school.

Acknowledgments

The design team received guidance from the following Georgia Tech faculty members:

1. Dr. Daniel P. Schrage
2. Dr. Robert G. Loewy
3. Dr. D. Stefan Dancila
4. Dr. Sathya V. Hanagud
5. Dr. Lakshmi N. Sankar
6. Dr. J.V.R. Prassad
7. Mr. R.J. Englar
8. Dr. Jimmy C. Tai
9. Dr. Vitali V. Volovoi
10. Mr. Andrew P. Baker
11. Dr. Amy R. Pritchett
12. Mr. Hoseung Lee
13. Mr. Naveen Gopal

Table of Contents

1 EXECUTIVE SUMMARY 1
2 INTRODUCTION 8
3 SYSTEM REQUIREMENTS AND CONSTRAINTS 8
3.1 General and System Capability Requirements 8
3.2 Mission Profile Requirements 9
4 DESIGN PROCESS 10
4.1 Introduction 10
4.2 Flowchart Description 11
5 AIRCRAFT CONFIGURATION DESIGN & SIZING 13
5.1 General Procedure 13
5.1.1 Preliminary Tiltrotor Sizing and Weight Analysis 13
5.1.2 Preliminary Conventional Helicopter Sizing and Weight Analysis 14
5.2 Vehicle Type Comparison and Selection 14
5.3 Tiltrotor Sizing Optimization 16
5.3.1 General Procedure 16
5.3.2 Mission Sizing Analysis and Results 16
6 CREW STATION DESIGN 19
6.1 Introduction 19
6.2 Cockpit Arrangement 19
6.3 Cabin Arrangement 21
6.4 Avionics and Mission Equipment Integration 23
7 FLIGHT CONTROL SYSTEM DESIGN 27
7.1 Smart Material Overview 27
7.2 FCS Tradeoff 27
7.2.1 Baseline: Heliflap^{TM} Actuation System 27
7.2.2 Concept One: Electromagnetic Actuation System 28
7.2.3 Concept Two: Piezo-Pneumatic Flap Actuation System 29
7.2.4 Concept Three: Piezo-Modulated Circulation Control 30
7.2.5 FCS Comparison and Selection 31
7.3 Circulation Control Overview 32
7.4 Flight Control System Configuration Design 33
7.4.1 Power Required 33
7.4.2 Configuration Design 36
7.5 Stability & Control Augmentation System (SCAS) 39
7.5.1 Desired System Responses 40
7.5.2 Precision Hover 40
7.5.3 Flight Management Computer 41
7.5.4 Required Sensors 41
7.5.5 Why Adaptive Control 41
7.5.6 Simulation of the Attitude Control Loop 42
7.5.7 Limit Detection and Avoidance System 44
7.6 FCS Subsystem Tradeoffs 45
7.6.1 Flight Control System Interface 45
7.6.2 Rotor Hub Design 45
7.6.3 System Communications – Fixed to Rotating Frame 46
7.7 Future Research Required (Technological Problem Areas) 46
7.7.1 Bimorph Bender Dynamics 46
7.7.2 Flow Dynamics 47
7.7.3 Control Authority During Autorotation 47
7.7.4 Rotor State Sensors 47
8 AIRFOIL DESIGN 48
9 STRUCTURAL DESIGN 50
9.1 Structures Overview 50
9.2 Airframe Description 50
9.3 Velocity-Load (V-n) Diagrams 52
9.4 Aeroelastic and Blade Analysis 53
9.5 Weight and Balance 53

Table of Contents (continued)

9.6 Damage Tolerance and Fatigue Life Analysis 55
9.7 Emergency Situations and Crashworthiness 56
9.8 Materials 56
10 PERFORMANCE RESULTS 58
10.1 Flight Performance 58
10.2 Static and Dynamic Stability 59
11 ENGINE SELECTION AND CHARACTERISTICS 61
11.1 Power Output and Related Assumptions 61
11.2 Additional Engine Characteristics 62
11.3 Technology Readiness 62
12 TILTROTOR CONVERSION 63
13 RELIABILITY/MAINTAINABILITY ANALYSIS 64
13.1 Reliability 64
13.2 Maintainability 68
14 COST ANALYSIS 69
15 AFFORDABILITY 72
16 MANUFACTURING 74
17 NOISE CONSIDERATIONS 75
18 CERTIFICATION 76
18.1 Certification Timeline 77
18.2 FCS Certification Considerations 77
18.3 Noise Certification Considerations 78
18.4 Crashworthiness & Safety Certification Considerations 79
19 ADDITIONAL APPLICATIONS 80
20 CONCLUSIONS 81

List of Figures

Figure 1: Required Mission Profiles 10
Figure 2: Design Process Flowchart 11
Figure 3: Three-View (foldout) 18
Figure 4: Cockpit Layout (foldout) 20
Figure 5: Internal Layout (foldout) 22
Figure 6: Electron Flight Display with Precision Pathway Terminal Guidance 23
Figure 7: Enhanced MFD-255 Displays 24
Figure 8: Kaiser Electronic HIDSS 25
Figure 9: S-76 Emergency Floatation Device 26
Figure 10: Heliflap™ Prototype Design and Specifications 28
Figure 11: Electromagnetic Actuation Schematics 29
Figure 12: Piezo-Pneumatic Actuation System Functional Diagram 30
Figure 13: Circulation Control Concepts 30
Figure 14: Circulation Control Using Piezoelectric Actuator 31
Figure 15: Circulation Control Power Required 35
Figure 16: Flight Control System Design (foldout) 38
Figure 17: SCAS Loop 40
Figure 18: Precision Hover Outer Loop 41
Figure 19: ACAH Control Loop (Pitch Axis Depicted) 42
Figure 20: Open Loop Stability Roots (Hover) 43
Figure 21: Step and Pulse Response Plots, Pitch Channel (Hover) 44
Figure 22: Limit detection and avoidance system 44
Figure 23: NACA 64-012 CC Airfoil w/ 0° Flap 49
Figure 24: Airfoil Twist Distribution 49
Figure 25: Structural Cutaway (foldout) 51
Figure 26: V-n Diagram (Helicopter Mode) 52
Figure 27: V-n Diagram (Airplane Mode) 52
Figure 28: Fan Plot (Gimbal Configuration) 53
Figure 29: Center of Gravity Limits 54

Table of Contents (continued)

Figure 30: Maneuver/Gust Load Limitation 55
Figure 31: Maximum Rate of Climb (Airplane Mode) 58
Figure 32: Autorotative Rate of Descent (75 knots) 59
Figure 33: Trim Condition for Forward flight (Helicopter Mode) 60
Figure 34: Trim Condition for Sideward Flight (Helicopter Mode) 60
Figure 35: Trim Conditions for Conversion 61
Figure 36: PT6C-67A Engine Cross-Section 62
Figure 37: Tiltrotor Conversion Corridor 64
Figure 38: FCS Fault Tree 65
Figure 39: FCS Failure Rate Distribution 66
Figure 40: Hazard Criticality Matrix 67
Figure 41: Functional Flow Block Diagram 67
Figure 42: Health and Usage Monitoring System (HUMS) 68
Figure 43: Certification Documents 76
Figure 44: Certification Timeline 77

List of Tables

Table 1: Requirements Response Matrix 9
Table 2: Tiltrotor Mission Profile Comparison (RF Method) 14
Table 3: Helicopter Design Solution Summary (RF Method) 14
Table 4: Vehicle Configuration Pugh Matrix 15
Table 5: Sizing Missions 16
Table 6: Weight Breakdown for Various Missions 17
Table 7: Basic Vehicle Characteristics 17
Table 8: Comprehensive Equipment List 26
Table 9: FCS Pugh Matrix 32
Table 10: Piezoelectric Bender Characteristics 37
Table 11: Control Augmentation Methods 40
Table 12: XV-15 Airfoil Sections 48
Table 13: Weight and Balance Statement 54
Table 14: FMEA for Piezoelectric Actuator System 66
Table 15: Cost Model Assumptions and Input 69
Table 16: Total Development Cost 70
Table 17: Total Average Cost per Aircraft (By System) 71
Table 18: Development and per Unit Aircraft Costs 71
Table 19: SAR Aircraft Characteristics 73
Table 20: SAR Aircraft Mission Cost Comparison 73

List of Equations

Equation 1: Lift Coefficient 33
Equation 2: Drag Coefficient 33
Equation 3: Momentum Coefficient 33
Equation 4: Blowing Power 35
Equation 5: Linear Twist Rate 49

1 EXECUTIVE SUMMARY

The Kingfisher air vehicle is an advanced technology tiltrotor aircraft that employs piezo-modulated circulation control (CC) in order to provide cyclic pitch. The vehicle is designed for performance, reliability, crashworthiness, and affordability, among other attributes.

Request for Proposal Summary

The mission requirements of the American Helicopter Society Request for Proposal (RFP) were the principle factors in establishing the design characteristics of the Kingfisher.[1] The RFP called for a search and rescue vehicle capable of performing three separate missions under specific conditions. The vehicle had to have a 600 nm range, a five-hour endurance capability, and had to be able to conduct a rescue in conditions similar to those in the novel, The Perfect Storm.[2] The vehicle was also to incorporate an advanced flight control system (FCS).

Vehicle Selection and Sizing

The design group considered a number of possible design solutions for this set of mission requirements. By using various decision tools (such as the Pugh Matrix) as well as various analytical tools (such as the Required Fuel Ratio Method for vehicle sizing), we established that the best candidate vehicle for this set of requirements was the tiltrotor.

A conventional helicopter configuration was considered but this was determined to have several significant limitations. With the fundamental speed limitation of a conventional helicopter, the mission time for this vehicle was determined to be over six hours. This long mission time forced the vehicle to carry an inordinate amount of fuel (over 5,000 pounds). Because of this fuel load, the conventional helicopter configuration had a gross weight of 17,035 pounds. The

[1] "2001 Request for Proposal (RFP) for Advanced Rotor Control Concepts," Sponsored by The Boeing Company and The American Helicopter Society International.
[2] Junger, S., The Perfect Storm: A True Story of Men Against the Sea, W.W. Norton and Company, May 1997.

gross weight of the vehicle could have been reduced by including aerial refueling during the mission. Although considered during analysis, the aerial refuel option for this vehicle is operationally improper. Due to the short response time for rescue missions, refuel coordination would be difficult and would add complexity to the mission. More importantly, however, is the fact that the U.S. Coast Guard (likely the principal user of the vehicle) has no aerial refuel capability and is not expected to in the future.[3]

After preliminary analysis using the Required Fuel Ratio Method, the tiltrotor aircraft was sized using the Georgia Tech version of the NASA/Boeing Program VASCOMP.[4] This program is a comprehensive sizing and performance program specifically designed to address tiltrotor aircraft. Based on the three required mission scenarios, the preliminary sizing analysis resulted in the data presented below.

Kingfisher Tiltrotor -- Major Characteristics			
Max Gross Weight	17,049 lbs	Rotor Diameter	27.65 feet
Empty Weight	12,502 lbs	Installed Power	4,250 HP
Fuel (w/o Auxiliary)	3,333 lbs	Cruise Airspeed	260 knots
Overall Length	44 feet	Max Airspeed	310 knots
Overall Width	65 feet	Max Range (Dry Tank)	700 nm

Flight Control Configuration

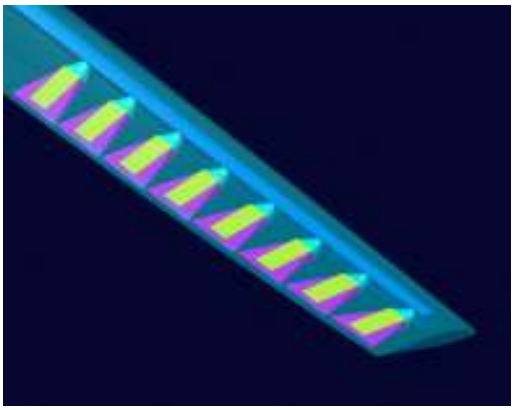
The design team considered a number of innovative methods to provide cyclic pitch for the vehicle. Some configurations considered were: single-stroke piezo flap actuators; various electromagnetic actuation methods; piezo-actuated energy storage methods; and piezo-modulated circulation control.

Of these possible configurations, piezo-modulated CC was selected as the most promising for this application. With this system, compressed air (from the engine [primary] and/or APU [secondary]) flows through a pneumatic slipring, through the blade spar (which acts as a conduit), and ultimately through slots in the trailing edge of the rotor blades (specifically, the outer 50% of each blade). This flow keeps the boundary layer attached (due to the Coanda effect) and can produce a tremendous amount of lift. Although this method of producing lift has been explored for more than 50 years, it has only been applied to replace the conventional tail rotor on production rotary wing aircraft. It has also been explored for fixed wing applications. The primary reason that it has not been applied to rotary wing aircraft is the fact that the flow must

[3] Storm, S., HH-60 Service Technician, Telephone Interview, USCG Aircraft Repair & Supply Center, Elizabeth City, North Carolina, February 2001.
[4] Schoen, A.H., Rosenstein, H., Stanzione, K.A., and Wisniewski, J.S., "User's Manual for VASCOMP II, Volume IV," Prepared by the Boeing Vertol Company, 1980.

be modulated at an extremely high frequency in order to provide cyclic control authority. Traditional methods of modulation were not fast enough to control the flow.

With recent advances in smart material technology, this fundamental problem can be mitigated. With a frequency response capability of more than 500 Hz, piezoelectric materials can provide adequate modulation authority. The Kingfisher uses these materials in the form of piezoelectric bimorph benders. In this configuration, two slabs of piezoelectric materials are fused to an insulator (or conductor depending on the specific design), which rests between the slabs. With an electric field applied to one slab and an opposite field applied to the other slab, a bending moment is created. The displacement caused by the bending moment is used to manipulate a shutter which then opens or closes an air duct, thus modulating the CC airflow. A flexible membrane provides the interface between the shutter and the duct inner wall surface. The Kingfisher uses eight of these bimorph benders for each of the rotor blades. The figure below illustrates the Kingfisher on-blade control system.



A small hub-mounted processor (HMP) will be located in the rotating frame on each rotor hub. Each HMP will consist of four identical and redundantly powered processors. These processors will serve as the single point through which bender signals pass (both command signals as well as system health signals). The use of the HMP allows for significant future system performance upgrades. Through software-only upgrades, the CC flow can be precisely managed. This will lead to improvements in noise emissions, vibrations, and other performance characteristics as well.

A mechanical feathering mechanism is used to provide collective control in helicopter mode and feathering pitch control in airplane mode. Although still a mechanical system, this feathering mechanism is much simpler than a traditional swashplate-based system. The CC blowing will only be used during helicopter mode. In order to avoid control coupling, the rotor must be capable of producing negative cyclic thrust. To do this, the rotor will blow air at a mean value and then deviate from this mean to produce cyclic thrust change. During transition, the blowing rates will gradually be

reduced until the transition is complete, at which time traditional airplane controls (ailerons, rudder, and elevators) will provide control.

With fewer moving parts, and thus fewer requirements for routine maintenance (e.g., lubrication, bearing replacement, etc.), this system offers a much simpler approach to cyclic control. Because of this simplification of the cyclic control system, the piezo-modulated control scheme yields predicted reliability levels comparable to or better than existing control systems. By using the reliability analysis program PRISM, the overall reliability of the FCS was calculated to be 0.97 failures per 10^7 flight hours.[5]

Control System

The spectrum of possible control methods for this FCS is very wide. In an effort to maintain simplification of the system, the design group determined that the best approach for control was a system that uses neural network adaptive control, which has been developed and matured at Georgia Tech. With this method, the control system adapts to changing circumstances within the vehicle and within the control system itself. Vehicle-mounted position and rate gyros provide the primary control signals for system controller adaptation.

Actual blowing rates will be scheduled based on control positions, vehicle state sensors (rate and attitude gyros, as well as rotor azimuthal position sensors), system health inputs, and environmental condition sensors. These environmental sensors include compressor discharge pressure, free air temperature, airspeed, and pressure altitude. These sensors will already be used by other systems (such as the engines) and so will not add complexity to the control scheme. Despite the large number of sensors required for control, the only sensors added beyond those of normal rotary wing aircraft will be the azimuthal position sensors (these are critical sensors and will require redundancy).

Based on the control method described above, there is no need to measure specific rotor states such as lead-lag motions (the stiff gimbaled rotor has a very small lead-lag motion) and flapping. Feathering pitch of the blades, however, will be known because of the mechanical nature of the feathering mechanism.

Static and dynamic control of the vehicle will be improved by the use of an Automatic Flight Control System (AFCS). Vehicle mounted gyros (and other sensors described above) will provide signals to the control system which will then command appropriate blowing levels to keep the vehicle at desired attitudes and angular rates.

A vehicle autopilot will be incorporated to improve long-term control stability and to decrease pilot workload. Features, such as a GPS navigation system to FCS interface, will provide autopilot course holding capabilities and turn coordination. Additionally, the vehicle will include a precision hover capability so that it can remain fixed over a point

during rescue operations. Although fixed over a point on the earth, the vehicle will still require inputs from the pilot since the evacuee could be moving in all three dimensions.

Another feature of the control system is that it will include a remote (cabin) hover control capability. With this remote device, a crewmember in the cabin area will have limited hover-only control authority to precisely maintain the vehicle's position over the rescue area.

Cockpit and Cabin Design

The Kingfisher is a dual-piloted aircraft with provisions for two cabin crewmembers (two para-rescuers or two medical personnel) and two patients (in litters). The cockpit will primarily use multifunctional displays (MFDs) as the method of relaying aircraft status, navigation information, and system degradation information to the pilots. The aircraft's navigation system will use a global positioning system (GPS) and an inertial navigation system (INS). Navigation and search pattern information will be provided by the MFDs and will be integrated with the aircraft's automatic flight control system. Avionics equipment will include UHF, VHF, FM, HF, and SATCOM radios. The aircraft will be instrumented and certified for flight under Instrument Flight Rules (IFR).

The cabin will contain crew and patient provisions as well as basic emergency medical equipment. The cabin will also house the rescue hoist and its controls, as well as over-water survival equipment and other emergency equipment such as parachutes.

Other Major Systems

Rotor System

The Kingfisher will use a four-bladed, gimbaled rotor system. A gimbaled system was selected primarily to accommodate the ducting for the CC blown air. Additionally, the gimbaled rotor eliminates the need for lead-lag dampers. Another advantage is that the gimbaled system will reduce the severity of control system failures. For example, if a single blade has a failure which requires shutting off the CC flow to that blade, the thrust vector could still be tilted with the control authority of the remaining blades, therefore maintaining cyclic control.

System Communications (Fixed-to-Rotating Frames)

Without sacrificing redundancy, the number of transmitted signals from the fixed to the rotating frame will be kept to a minimum. Individual blades will share signal paths. The signals to be passed between the fixed and rotating frames (per rotor) include: two control signals (for redundancy), which command the appropriate HMP to position the bimorph benders correctly for flow modulations; two shutoff valve channels (for redundancy); a health monitoring signal channel

[5] "PRISM User's Manual Version 1.0," Prepared by the Reliability Analysis Center, Rome, New York, 2000.

(the redundant signal is incorporated in the control signals); and two power channels (for redundancy). This is seven signals per rotor beyond normal signal transmission requirements (such as blade de-ice signals). To provide for these communication requirements, the system will use a standard slipring arrangement. All rotating frame components are low power so there will be no need for a high-power slipring.

Structures

After considering a number of possible structural materials for the Kingfisher, the design team decided that composites were predominantly the best option. These materials offer good performance in terms of strength-to-weight ratio. More importantly, their resistance to corrosion and corrosion fatigue are important attributes given the vehicle's operating environment.

The Kingfisher will be designed to provide maximum survivability in crash scenarios. The vehicle will incorporate features such as: crashworthy fuel tanks and seats; fire suppression equipment; crash-attenuating structural components; and non-intrusive main landing gear struts.

Flight Control System Reliability

Reliability of the FCS is perhaps the single most crucial aspect of the vehicle design. As with any new system or technology applied to aircraft, safety and dependability must be proven beyond doubt. The FCS was modeled, from the cockpit to the final ducting of the rotor blades (including sensors, control computers, and associated hardware), using the reliability simulation program PRISM. With this comprehensive model, the FCS was calculated to have a reliability of 0.97 failures per 10^7 flight hours. This level of reliability is within the RFP requirement of 1 failure per 10^7 flight hours. This figure, however, is based on the preliminary design data and so a much more thorough (empirically based) analysis will have to be conducted in order to determine specific component failure rate tolerances.

Cost and Affordability

Development and manufacturing costs were calculated using a PC-based cost model obtained from Bell Helicopter.[6] Previously determined vehicle-specific data such as component weights and materials, as well as many other design features, were applied to the model. Based on this data (and production data from the RFP), the system was determined to have a total development cost of $465 million. Unit cost, which includes development cost amortized over the 300 vehicles, was calculated to be $9.40 million per aircraft (year 2000 dollars). If the Kingfisher were to be produced as a variant of the Bell-Agusta 609, the amortized unit aircraft cost would be $8.87 million.

[6] "PC Based Cost Model Developed by Bell Helicopter", Bell Helicopter, 1999.

Although somewhat more expensive in terms of acquisition cost (relative to comparably-sized conventional helicopters), the Kingfisher's significant improvements in speed, range, and endurance offer considerable savings in terms of operating affordability, defined as the ratio of operational effectiveness to the cost of achieving the operational effectiveness. The Kingfisher will take less time to reach a rescue area and will be able to search a greater area of ocean on a single sortie. With this improved performance, the Kingfisher is expected to reduce operating cost by more than 50% compared to current U.S. Coast Guard rotary wing aircraft. This increased performance capability also reduces the total number of airframes required for a given level of mission capability.

Certification

The most difficult obstacle to overcome in the certification of the Kingfisher is its incorporation of the advanced technology FCS. To mitigate potential certification problems, the design was intentionally kept as simple as reasonably possible. The aircraft will have to be certified primarily under FAR Parts 25, 29, and XX (although it must meet certification requirements of other publications as well). To comply with these certification requirements, the aircraft is expected to undergo a seven-year certification plan. Although two years longer than standard certification periods, this type of planned extension was granted for the BA-609 and could be reasonably expected for this vehicle as well.

Conclusion

Simple, efficient, and cost-effective, the Kingfisher is a well-suited vehicle for short- and medium-range search and rescue missions. It meets the desired capabilities of the Coast Guard SAR pilots who are required to conduct these missions. Its advanced FCS is a prudent step forward from traditional controls to smart material controls. This FCS relies on the judicious and pragmatic application of advanced technology rather than on complexity for complexity's sake. Though a flight control system could be devised with a myriad of exotic materials, all undulating in harmony at the direction of the on-board Cray computer, the aircraft controlled by that FCS would most likely never fly. The Kingfisher, conversely, is an aircraft that very well could be designed in detail, certified, produced, and could ultimately perform its mission.

2 INTRODUCTION

Rotary wing aircraft have used a wide variety of control methods in the years since Paul Cornu's first piloted helicopter flight in 1907.[1] Although a large number of methods were conceived, virtually all modern rotary wing aircraft rely on the swashplate as the method of achieving control. With recent improvements in computer technology, control theory, and, especially, smart material technologies (e.g., piezoelectrics, shape memory alloys, and magnetostrictives), other control methods are becoming more and more feasible. The Kingfisher represents a first step in this direction – from traditional controls to advanced on-blade controls.

The Kingfisher is a dual-piloted tiltrotor aircraft that uses an innovative method for controlling the cyclic pitch of its rotor blades. This control method capitalizes on the simplicity of circulation control and the advancements in piezoelectric materials. Compressed air from the engines (primary source) or APU (secondary source) travels through a series of ducts and manifolds to the main spar of each blade. The spar leads to eight ducts (running in the chordwise direction) which each lead to a chamber with a piezoelectric bimorph bender. The benders modulate the compressed air, which flows out of slots in the trailing edge of the blade (the outer 50% of each blade is slotted). This flow produces lift through the Coanda effect. Information is transferred between the automatic flight control system (AFCS) computer in the fixed frame to a small hub-mounted processing (HMP) in the rotating frame. Fly-by-wire technology provides the interface between the pilot and the control surfaces.

The Kingfisher is powered by two 2,125 HP MCP-rated engines which drive the two four-bladed, gimbaled, hingeless rotor systems. The Kingfisher provides state-of-the-art cockpit stations and incorporates numerous methods and technologies for optimizing crew interface and enhancing mission performance.

This design proposal meets or exceeds the 2001 Advanced Rotor Control Concepts Request for Proposal (RFP) requirements.[2] The Kingfisher, with a gross weight of 17,049 lbs, a cruise speed of 260 knots, and a mission radius of 350 miles (without refueling), provides an ideal platform for search and rescue (SAR) operations.

3 SYSTEM REQUIREMENTS AND CONSTRAINTS

3.1 General and System Capability Requirements

Table 1 contains the RFP general and system capability requirements, the Kingfisher design solutions to those requirements, and the proposal sections which address those design solutions.

General Requirements	Design Solution	Section
Dual-Piloted VTOL Rotorcraft	Achieved	6.2
High Value Technologies: Airframe	Achieved	9.2
High Value Technologies: Propulsion	Achieved	11
High Value Technologies: Human Factors Engineering	Achieved	6
Dramatically Improve Performance	Achieved	10
Dramatically Improve System Commonality	Achieved	13.2
Perform SAR Mission, Rescuing Two People	Achieved	5
Mission Radius: 300 nautical miles (nm)	Achieved	5
Conditions: Instrument Flight Rules (IFR) IAW applicable FARs	Achieved	6
First Aircraft Delivered in 2015	Addressed	16
Average Production Rate of 4 Aircraft/Month	Addressed	16
De-ice Equipment on in Known Icing Conditions	Achieved	6
Fixed Useful Load Comprehensive List	Achieved	6
Required System Capabilities	**Design Solution**	**Section**
Power-Off Glide/Autorotation Capability	Achieved	10
Desired: Manual Rotor Blade Folding (desired)	Addressed	13.2
Cabin Storage Capacity: 2 crew, 2 patients	Achieved	6
Authorized Flight Envelope: Consistent with appropriate FARs	Achieved	10
Cruise Transient Turn Capability (Min. = 30^{o} Bank Turn)	Achieved	10
OEI OGE Hover Capability (60% fuel, full payload, SL, ISA $+20^{o}$C)	Achieved	5
Reliable Unassisted Self-Starting Capability	Achieved	11.2
Adverse Weather, Night Capable	Achieved	6
Designed to Facilitate Basic Aircraft Maintenance	Achieved	13.2
Good Crashworthiness Design	Addressed	9.7, 18.4
Design for Low Noise to Minimize External Noise/Internal Noise	Addressed	17
Assume Emerging Turboshaft Engine Technologies	Achieved	11

Table 1: Requirements Response Matrix

3.2 Mission Profile Requirements

The system must be sized to meet the requirements of the range, endurance, and final evaluation missions summarized in Figure 1. The final evaluation mission, which is the primary mission for this proposal, is loosely based on the SAR mission flown in the novel The Perfect Storm.[3] This final evaluation mission will be referred to as the primary mission throughout the remainder of this proposal.

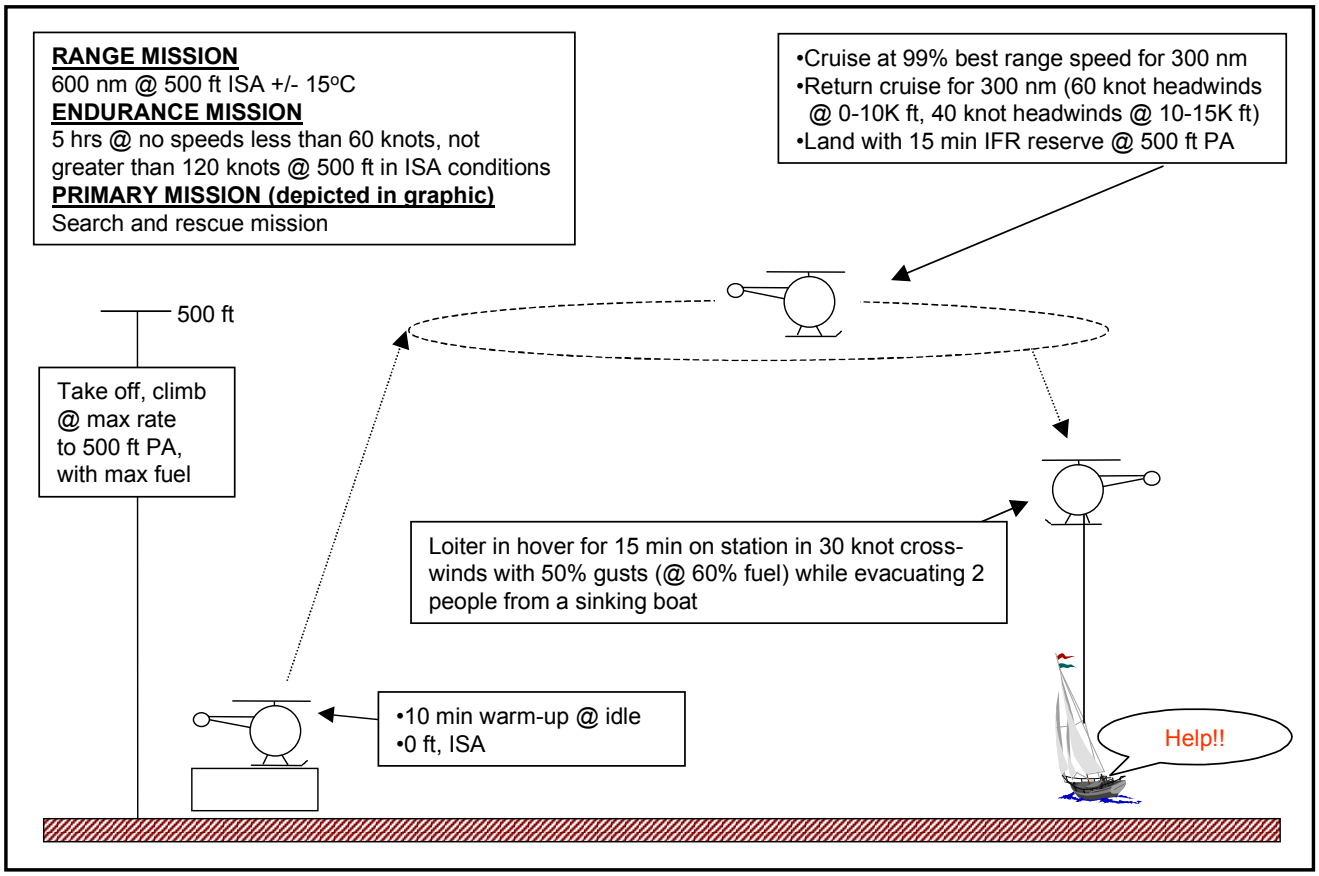


Figure 1: Required Mission Profiles

4 DESIGN PROCESS

4.1 Introduction

Flight vehicles are extremely complex systems that depend on input and analysis from a variety of engineering disciplines. Decisions and analysis performed on one particular aspect of the design can have a tremendous effect on many other aspects of the design. A comprehensive and clear design process was established to synthesize the complex and interwoven design challenges. This design process was fundamentally iterative such that, with each iteration, the design gained detail and fidelity and grew closer to its end state. Depicted in Figure 2 is the design process. The feedback loops (dashed lines) highlight the iterative nature of the process, by which late-stage design information is fed back into early-stage design steps. Following the flowchart are brief descriptions of the steps used in the process (including descriptions of the major simulation tools used). The order of the descriptions does not necessarily follow the order of the design (please refer to the flowchart for task sequence).

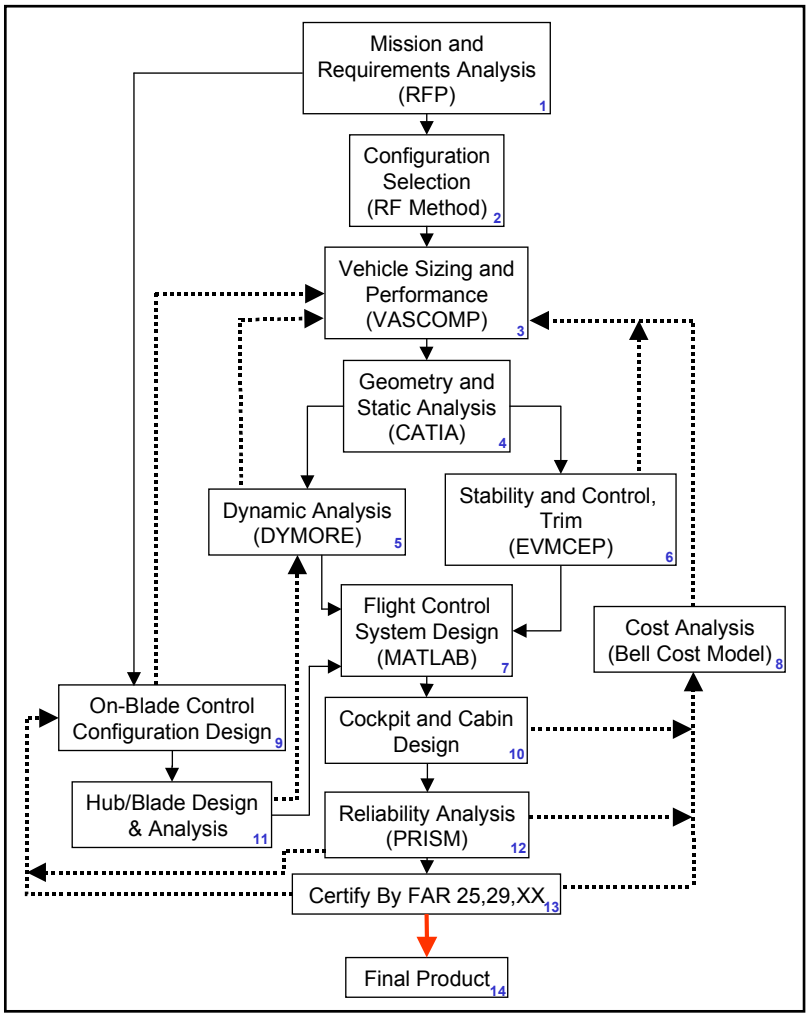


Figure 2: Design Process Flowchart

4.2 Flowchart Description

1. Mission and Requirements Analysis: During this early stage of the design, the objective was to define the problem and generate feasible alternatives.

2. Configuration Selection: The goal of this phase was not necessarily to determine specific detailed design characteristics, but rather, on a macro-level, to determine some of the key aspects of the design (such as vehicle type). Analytically, the Required Fuel Ratio (RF) Method was used to size various candidate vehicles.[4] With this "first-cut" information, Pugh Matrices and other decision-making tools were then used to select the vehicle type and other design characteristics. Since a tiltrotor was selected, the remaining modeling and simulation programs focus on this configuration.

3. Vehicle Sizing and Performance: After determining the fundamental configuration of the vehicle, more insight into its potential size, geometric characteristics, and performance attributes was required. The Georgia Tech version of the NASA/Boeing Program VASCOMP (V/STOL Aircraft Sizing and Performance Computer Program) provided this

insight.[5] This program sized the vehicle based on the mission inputs. It calculated system characteristics and parameters based on the mission profile and the program's historical database. This program produced outputs that included geometric information, component weights, preliminary cost analysis, and performance characteristics.

4. Geometric and Static Analysis: A three-dimensional virtual model of the aircraft was created in order to determine structural weights, moments of inertia, airframe static structural performance and strength analysis, and other design characteristics. This model allowed for internal space programming (for useful load items and for system components) and for general visualization. The primary tool for this stage of design was the program CATIA (Computer Aided Three-Dimensional Integration Application).[6] CATIA generated an editable virtual product geometry.

5. Dynamic Analysis: The principal objective during this phase of the design was to create a model of the hub and rotor system. The Georgia Tech non-linear multi-body dynamics code, DYMORE, was used to create this model.[7] This program analyzed the dynamic performance (including bending modes and aeroelastic effects) of the hub and rotor system.

6. Stability and Control/Trim Analysis: Generalized trim solutions for the vehicle were obtained during this design phase. Additionally, the stability and control of the vehicle was analyzed. To do this, EVMCEP (Evasive Maneuver Criteria Evaluation Program) was used.[8] This program created a six degree of freedom flight model to analyze the flight handling qualities.

7. Flight Control System Design: After gaining insight into the basic vehicle handling qualities, the functions and performance of the FCS were developed and refined. The system was modeled in MATLAB.[9] The dynamic response of the vehicle for various flight control inputs was also analyzed.

8. Cost Analysis: Development and production costs were analyzed throughout the design process. To conduct detailed quantitative cost analysis, a rotorcraft cost model obtained from Bell Helicopter was used.[10] This model, based on V-22 data as well as projected BA-609 data, uses a large variety of inputs to predict both development and production costs.

9. On-Blade Control Configuration Design: Various configuration options for the FCS were explored using the decision-making tools mentioned previously. The most appropriate FCS configuration for the vehicle was selected.

10. Cockpit and Cabin Design: The form and function of the cockpit and cabin areas were developed and refined. The focus was on major systems integration such as avionics equipment, navigation equipment, mission equipment, and controls and displays. CATIA was used for cockpit/cabin design layout and analysis.

11. Hub/Blade Design & Analysis: The principal objective during this portion of the design was to analyze the aerodynamics and dynamics of the hub/rotor system with particular emphasis on the integration of the FCS. For

aerodynamic analysis, a Georgia Tech developed two-dimensional Navier-Stokes solver was used. The goal, through iterative design, was to optimize the hub/blade design for both helicopter mode and for fixed-wing mode.

12. Reliability Analysis: The reliability of the vehicle and its various systems (with emphasis on the FCS) was modeled and predicted. The program PRISM was the main tool.[11] This program performed system-level failure rate assessments based on an extensive component failure rate database. By identifying critical components and elements of the design, improvements were designed. Ultimately, an FCS reliability of less than one failure per 10^7 flight hours was demonstrated.

13. Certify By FAR 25, 29, XX[12]: The vehicle was designed to meet all applicable certification requirements, with particular emphasis on the FCS, noise, and safety and crashworthiness certification considerations. Certification procedures to demonstrate compliance through design, analysis, testing, and evaluation were planned and developed.

5 AIRCRAFT CONFIGURATION DESIGN & SIZING

5.1 General Procedure

Using qualitative methods, the two best candidate vehicles for this mission were determined to be the conventional helicopter and the tiltrotor. Before these candidate vehicles could be sized, the useful load had to be defined. After some research, the vehicle's useful load was calculated to be 2,482 lbs (includes both fixed and non-fixed useful load items). The vehicles were assumed to use Jet A fuel which has a density of 6.75 lbs/gal.

The RF Method was used to size the vehicles (using comprehensive empirical spreadsheets). With this method, one iterates for design solutions by balancing the power required with the power available and by balancing the fuel required with the fuel available.

5.1.1 Preliminary Tiltrotor Sizing and Weight Analysis

The tiltrotor RF sizing spreadsheet was based on the V-22 Osprey. This spreadsheet was further calibrated by using weight breakdown information on the BA-609. Based on the RFP guidance, engine performance was improved by assuming a 25% reduction in Specific Fuel Consumption (SFC) and a 40% improvement in power-to-weight ratio.

Standard tiltrotor design parameters, such as lift-to-drag ratio during cruise, cruise efficiency, and hover efficiency, were used in the model. Table 2 depicts design solutions that met the performance requirements of the three mission scenarios described in the RFP. In the primary mission, the aircraft would ingress at a cruise speed of 200 knots at 500 feet altitude to the sinking boat and then egress at 10,000 ft.

	RANGE	ENDURANCE	PRIMARY
PROPULSION			
Total HP installed (MCP)	4,400	4,000	**5,000**
Power Loading (lbs/shp) OEI	4	4	**3**
HP required OEI (ERP)	2,859	2,659	**3,141**
Power Loading (lbs/shp) OEI	5	5	**5**
MISSION			
Cruise Speed (kts)	250	120	**200**
Range (nm)	663	603	**663**
Cruise Time (hrs)	3	5	**3**
Fuel Weight (lbs)	2,489	2,048	**2,722**
VEHICLE			
TOGW (lbs)	15,704	14,603	**17,255**
Empty to GW Rato ϕ	0.673	0.683	**0.665**
Disk Loading ω (lbs/sqft)	17	17	**17**
Useful Load (lbs)	2,238	2,238	**2,620**

Table 2: Tiltrotor Mission Profile Comparison (RF Method)

5.1.2 Preliminary Conventional Helicopter Sizing and Weight Analysis

In order to assess the size and component weights of a conventional helicopter designed for the missions of the RFP, an RF spreadsheet based on the UH-60 was used. The propulsive characteristics described in the tiltrotor sizing section were used for the calculations. Design solutions were obtained after calibrating and then validating the RF spreadsheet (by comparing its output with two actual helicopters). These design solutions were optimized to obtain the minimum gross weight for the vehicle. Also analyzed was the scenario in which the helicopter conducts one air-to-air refuel enroute to the rescue site. The refuel was considered to occur at a point such that the helicopter could return to its point of origin if the refuel failed (this point corresponded to ¾ of the 300 mile leg enroute to the rescue area). The results of these calculations are presented in Table 3.

Configuration	Refuel	Gross Weight (lbs)	Installed Power (HP)
Basic Helicopter	No	19,035	4,445
Basic Helicopter	Yes	15,500	3,674

Table 3: Helicopter Design Solution Summary (RF Method)

5.2 Vehicle Type Comparison and Selection

The design team analyzed the two vehicles, both qualitatively and quantitatively, using a Pugh Matrix (depicted in Table 4).

Pugh Matrix Configuration Selection			Alternative Concepts		
			BASELINE UH-60Q	1 Advanced Helicopter	2 Tiltrotor
AFFORDABILITY	Performance	Range	DATUM CONCEPT	1	1
		Endurance		1	1
		Cruise Speed		0	1
		Maneuverability		1	1
		Fuel Required/TOGW		-1	1
	Feasibility	Weight		-1	1
		Crashworthiness		0	0
		Tech. Readiness Level		0	-1
	Costs	Total System Complexity		0	-1
		RDTE		0	-1
		Operation		1	1
		Reliability		0	0
			Σ + 1	**4**	**7**
			Σ - 1	**2**	**3**
			Σ 0	**6**	**2**

Table 4: Vehicle Configuration Pugh Matrix

The conventional helicopter has several positive characteristics, but the negatives outweigh these positives. Most prominent among its positive attributes is the fact that conventional helicopter technology is more mature than that of the tiltrotor. The conventional helicopter's main limitation, however, is its cruise performance. Given the long mission range and the return-leg headwind, the conventional helicopter would take over six hours to complete the mission (at 150 knots). This is simply too long of a mission time given the urgency of search and rescue type missions. For six flight hours, the conventional helicopter would consume over 5,000 lbs of fuel. This is an inordinate amount of fuel for a medium-sized helicopter to carry. In fact, the size of the vehicle itself is driven completely by this enormous fuel requirement. In contrast, the tiltrotor would require about 2,700 lbs of fuel to complete the mission. Although air-to-air refueling was considered for the helicopter, this is, operationally, a very poor configuration. Search and rescue type missions, similar to medical evacuation missions, must be planned and executed as quickly as possible. Air-to-air refuel coordination would add an additional and unnecessary level of complexity to an already complex mission. Further, the U.S. Coast Guard (assumed to be the principal user of the vehicle) has no air-to-air refuel capability and is not expected to in the future.[13]

The tiltrotor proved to be the best vehicle for this set of missions, primarily based on its superior cruise performance. Although a relatively new type of aircraft, the tiltrotor will rapidly advance in technology level as industry begins producing the first commercial tiltrotor aircraft, the BA-609.

5.3 Tiltrotor Sizing Optimization

5.3.1 General Procedure

After selecting the tiltrotor as the vehicle configuration, the next goal was to develop a higher fidelity model to analyze the vehicle's characteristics and performance. The sizing program, VASCOMP, was used for this analysis. VASCOMP is a sophisticated sizing tool that requires a large amount of data in order to perform its sizing routines. In addition to the large number of inputs, the program must also be calibrated against some real vehicle to ensure the validity of the output. Detailed weight information on the BA-609 was unavailable, so the XV-15 served as the primary VASCOMP model (the V-22 was not used since it is "militarized" and has features, such as the folding pylon, which would lead to inaccuracies). The XV-15's design data, however, was compiled more than 20 years ago. Consequently, this information does not reflect the many technology advancements made after XV-15 design and production. Additionally, since the XV-15 was an experimental prototype, it was never optimized following flight-testing. To adjust for these problems, correction factors were used in VASCOMP. Specifically, the correction factors for fuselage, wing, rotor, and flight control weights were decreased by ten percent.

The engine weight and performance was based on the PT6C-67A, the engine designed for use in the BA-609. The Kingfisher will use a derivative of this engine, termed the PT6C-KF (please see Section 11 for a detailed description). After assuming the power-to-weight and SFC improvements due to IHPTET advancements, the PT6C-KF will have a 2,125 HP MCP rating and a weight of 408 lbs per engine.

5.3.2 Mission Sizing Analysis and Results

Many sizing trade studies were performed in order to identify the most stringent vehicle requirements. Initially, the trade studies identified by the RFP served as a basis for focusing the design team's efforts. To size the vehicle, the mission parameters summarized in Table 5 were used. Other trade studies were also performed to optimize the vehicle for disc loading, wing loading, cruise speed, and other performance characteristics. Note that the return altitude in the "Primary" column is 15,000 feet. This higher altitude was determined, through VASCOMP analysis, to be the optimal choice based on slower head winds and improved engine performance.

Parameter	Range Mission	Endurance Mission	Primary Mission
Range (nm)	600	N/A	600
Time (hours)	N/A	5	N/A
Altitude (ft)	500	500	Ingress: 500, Egress: 15K
Temp (^{o}C)	ISA +/-15	ISA	Variable
Speed (kn)	Best Range	60<Max End Vel<120	Best Range
Head Wind (kn)	0	0	Egress only: 40 kn (<10K), 60 kn (10-15K)

Table 5: Sizing Missions

The weight breakdown for the vehicle is summarized, by mission, in Table 6.

MISSION WEIGHT BREAKDOWNS				
SUBSYSTEM	**RANGE**	**ENDURANCE**	**PRIMARY**	**FINAL**
Engines	780	816	759	816
Fuselage	1,808	1,766	1,899	1,904
Wings	800	866	1,005	1,015
Nacelle	302	305	300	305
Empenage	277	297	310	313
Alighting Gear	588	642	679	690
Flight Controls	1,178	1,271	1,335	1,355
Hydraulic/Electrical	458	490	512	519
Instruments	286	286	286	286
Air Conditioning/De-ice	303	303	303	303
Personal Accom.	423	336	423	423
Rotor System	831	911	966	983
Drive System	1,161	1,268	1,342	1,365
Fuel System	280	441	335	345
Engine Access	250	262	258	269
AF Electronics	343	343	343	343
Vehicle Empty Weight	10,067	10,603	11,055	11,234
NOTE: The Maximum Weights Have Been Highlighted				

Table 6: Weight Breakdown for Various Missions

With the exception of the fuel system weight, the component weights for the final vehicle are all higher than for any of the individual missions. In order to complete the endurance mission, the vehicle would require 1,170 pounds of auxiliary fuel. This fuel would be stored in an auxiliary fuel system located in the aft portion of the cabin. In accordance with the RFP, the vehicle does not need to conduct a rescue operation during the endurance mission so the two cabin crewmembers, the two evacuees, and the rescue equipment would be removed to accommodate this fuel.

The final configuration characteristics are summarized in Table 7.

PROPULSION		**ROTOR**		**WEIGHT**		
NUMBER OF ENGINES	2	DIAMETER (ft)	27.65		**lbs**	**% Total**
PWR/ENGINE (H.P.)	2,125	NUMBER OF BLADES	4	EMPTY	11,234	66%
WEIGHT/ENGINE (lbs)	426	C_T/σ	0.125	FIXED USEFUL	1,269	7%
AERODYNAMICS		DISC LOADING (lb/sqft)	14.2	OPERATING	12,503	73%
WING LOADING (lbs/sqft)	84.3	TIP SPEED (fps) cruise	600	PAYLOAD	1,213	7%
EQUIV. FLAT PLATE DRAG (sqft)	7.392	TIP SPEED (fps) hover	650	FUEL	3,333	20%
L/D MAX	10.74	σ	0.121	GROSS	17,049	100%

Table 7: Basic Vehicle Characteristics

Figure 3 (foldout, pg. 18) depicts the Kingfisher in three-view with the major dimensions illustrated.

Figure 3: Three-View (foldout)

6 CREW STATION DESIGN

6.1 Introduction

We conducted numerous interviews with Coast Guard, Air Force, and Army SAR and MEDEVAC pilots in an effort to design the ideal cockpit and cabin crew stations. Included in our interviews was Air Force Lieutenant Colonel (LTC) Dave Ruvola, who flew the "Perfect Storm" mission in 1991. We also drew from the experience of three of our design group members who are U.S. Army aviators with an average flight hour experience of 1000 hours. These aviators have flown, collectively, the UH-1H, AH-1F, OH-58A/C/D, UH-60A/L and AH-64A helicopters. According to the Coast Guard pilots interviewed, the perfect SAR aircraft would have the HH-65A Dolphin's avionics, the HH-60J Jayhawk's performance, and the HH-3F's cabin space.[14] These ideals were integrated in the design of the Kingfisher.

6.2 Cockpit Arrangement

The Kingfisher's cockpit layout is depicted in Figure 4 (foldout, pg. 20). The pilot and copilot positions are on the right and left sides of the cockpit, respectively. Each pilot has a dual set of Instrument Flight Rule (IFR) capable flight instruments. All instrumentation and aircraft lighting is night vision device (NVD) compatible. As part of the glass cockpit configuration, the instrument panel contains multifunction displays (MFDs), a flight director panel, and support system displays. The pilots share lower consoles, upper consoles, and the center instrument panel. The upper console contains electrical system switches, cabin lighting controls, heating and air conditioning controls, and circuit breaker panels. The lower console contains the flight management system panels in addition to the avionics control panels. Emergency back-up instruments include analog attitude indicators, a barometric altimeter, a magnetic compass, and a fuel gauge (during normal operations, these functions are embedded in the MFDs). The Kingfisher crew stations are designed to accommodate 5th percentile female through 95th percentile male pilots (per MIL STD 1472E).[15]

The pilot and copilot stations are each equipped with a cyclic stick, collective stick, and foot pedals. Each cyclic stick grip contains a trim switch, a cargo release switch, a radio/ICS switch, and MFD function switches. Each collective stick grip contains landing and search light controls, an emergency cargo hook switch, and a guarded nacelle conversion switch. The switches on the cyclic and collective sticks assist the pilots during high workload situations. The engine power control levers are located in the center/forward portion of the upper console. Either pilot can perform all flight duties for helicopter, airplane, or conversion modes (or they can share the workload to reduce fatigue). In helicopter mode, the pilot uses the collective stick to control power (with the power control levers set at 100% rotor speed), and the

Figure 4: Cockpit Layout (foldout)

cyclic stick to control attitude. The pedals control yaw rate through differential tilting of the thrust vector. In airplane mode, the pilot uses the collective to control proprotor pitch and the power control levers to control engine speed. The cyclic stick becomes a conventional fixed-wing control stick and the pedals control the rudder.

The pilot and copilot access the cockpit through side doors, one on each side of the cockpit. Emergency release handles are located on the inside frame of each door. Pulling these handles will jettison the cockpit doors in an emergency. Crashworthy seats, coupled with cockpit air bags, increase pilot and copilot survivability during crash landings. Five-point seat restraint is provided by a shoulder harness, lap belt, and crotch belt. Fire detection and fire extinguishing systems are installed to allow the pilot to detect and extinguish engine and/or APU fires.

Miscellaneous crew equipment provisions include a Helmet Integrated Display Sight System (HIDSS), electronic kneeboard wireless receivers, map lights, portable fire extinguishers, fresh air outlets, and an oxygen system.

6.3 Cabin Arrangement

The cabin area provides accommodations for two additional crewmembers (normally the para-rescuers) and two litters (which are removable for additional passenger seating). Please see Figure 5 (foldout, pg. 22) for the aircraft's internal layout. The Kingfisher has a cabin volume of 315 ft^3. This is very similar in size to other SAR aircraft like the HV-609 (258 ft^3), HH-60 (387 ft^3), and HH-65 (178 ft^3). The cabin is also the location for the EMS, rescue, and emergency/survival equipment. The cabin equipment may be removed and replaced easily so that the aircraft can be quickly configured to meet a variety of missions.[16] The main entrance to the cabin is through the aft sliding door on the right side of the compartment. Unlike the HH-60 Jayhawk, the cabin door is not restricted by the external fuel tanks and allows easy entry and egress from the aircraft. The cabin door has emergency release handles with jettison capability. The cabin console contains an intercom/avionics control panel and a remote hover control panel located forward of the cabin door. As recommended by LTC Ruvola, the cabin will have separate intercom system (ICS) capability to allow the cabin crewmembers to communicate freely without disrupting the pilot communications/duties.[17] Emergency equipment located in the cabin includes parachutes, floatation devices, survival kits, and fire extinguishers. Each cabin seat is designed with a cable-supported steel tube assembly that will reduce injury in a crash. The five-point seat restraint in the cabin compartment gives wearers limited freedom to move about the cabin compartment.[18] For movement throughout the entire cabin, the crewmember will wear a monkey harness. Additional cabin compartment provisions include utility lights, fresh air outlets, and an oxygen system.

Figure 5: Internal Layout (foldout)

6.4 Avionics and Mission Equipment Integration

The Kingfisher cockpit is designed to provide the pilots with the most modern integrated full glass cockpit and flight management system. It automates a multitude of aircrew tasks, thus reducing pilot workload and enhancing situational awareness. The arrangement and location of instrumentation complies with MIL STD-250.[19]

The pilot and copilot have two MFDs in each of their stations. The MFDs provide three-dimensional flight instrumentation, navigation sensor management, weather radar, search radar, storm scope, radio navigation management, and aircraft performance.[20] Each MFD has three display configurations: the electronic flight display (EFD); the weather navigation display; and the hover display. The displays are interchangeable to allow pilots to customize the display arrangement for optimum performance.

In order to reduce tracking errors and pilot workload, a predictive flight path, primary flight instrumentation, and aircraft performance symbology were incorporated in the EFD. The predictive flight is provided by the Precision Pathway Terminal Guidance (PPTG) "Tunnel in the Sky" symbology. This symbology system provides a view of the aircraft's position relative to the desired flight path. Figure 6 is a PPTG display with Synthetic Vision (SYNVIS) symbology. The "Tunnel in the Sky" symbology provides anticipatory pathway and field flow from 400'H x 500'W and reduces in size with terminal instrument procedures (TERPS) criteria to 100'x125' at runways. The "Tunnel in the Sky" concept also incorporates a quickened flight path vector (FPV) (developed at the Technical University of Delft) and a 400'x600' predictor command (developed at the Technical University of Munich).[21] Depending on the mission profile, each pilot may turn off the "Tunnel in the Sky" symbology in the EFD.

Figure 6: Electron Flight Display with Precision Pathway Terminal Guidance

Each MFD is capable of integrating navigation sensors with worldwide navigation databases. The MFDs will incorporate navigational aid instruments, weather radar, search radar, ground proximity warning devices, and a cockpit alerting system. The Kingfisher is equipped with TACAN, VOR, DME, ILS, GPS, Doppler, INS, a differential GPS precision landing system, and radar altimeters to best accommodate SAR missions.[22]

The capabilities of the existing Rockwell Collins 5ATI Multifunction Display (MFD-255) [see Figure 7] will be expanded to meet SAR requirements.[23] The current MFD-255 displays FLIR, digital map, and video inputs. The left display in Figure 7 shows an enhanced navigational display concept which provides obstacle avoidance information, weather and wind shear conditions, and navigational chart information. The mission planning data from the navigation display is linked to the "Tunnel in the Sky" MFD which allows the pilot to guide the aircraft to a safe altitude and direction away from obstacles and adverse weather conditions. The tunnel with SYNVIS is aligned to real-time environmental conditions and is calculated by the flight management system (FMS).[24] The right display in Figure 7 shows an enhanced MFD-255 hover display superimposed on video feedback from the TV camera (FLIR/day/night) mounted under the nose of the Kingfisher. This real-time hover symbology provides situational awareness to the pilot.

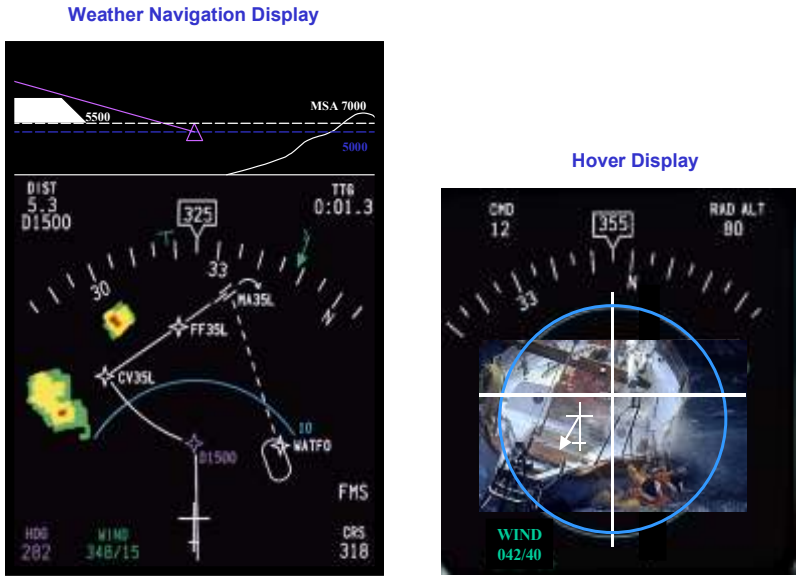


Figure 7: Enhanced MFD-255 Displays

The pilot and copilot share the center MFD located on the instrument panel. This is a two-screen MFD with flight and waypoint planning, search and rescue patterns, integrated aircraft instruments, an FMS, and health and usage monitoring systems (HUMS) (see Figure 4 [foldout, pg. 20]). SAR pilots noted the importance of the automated SAR search pattern and weather radar capabilities. Again, the screen displays are interchangeable to allow pilots to customize the display

arrangement. The information from the integrated aircraft instruments and flight mission data is communicated in real-time to other instruments in the aircraft as well as back to the SAR headquarters agency.

On a SAR mission, the pilot on the flight controls will select the EFD and hover display. The copilot will select the EFD and the weather navigation display to assist the pilot flying the aircraft.

The Kingfisher has a robust communications suite that includes three radios, each capable of FM, UHF, VHF, HF, and SATCOM communications. The communications suite also incorporates a wireless voice and internet system. The dual communication management systems, located on the lower console, allow the pilot and copilot independent access to a wide variety of communication systems which can be tailored to support various mission profiles. The wireless helmet integrated display sight system (HIDSS), depicted in Figure 8, provides communication and flight instrumentation capabilities to the pilots and crewmembers. The HIDSS allows cabin crewmembers to communicate without interference from normal ICS chords. The HIDSS will provide binocular night vision enhanced by the third generation FLIR. With this arrangement, the crew will have a 45º night field of view. This is a significant improvement over current systems, such as the ANVIS-6. The HIDSS will be designed within para-rescue headgear to be waterproof.

Figure 8: Kaiser Electronic HIDSS

The Kingfisher is equipped with the latest SAR equipment. The rescue hoist, which can lift up to 600 pounds, is mounted inside the crew cabin station next to the main cabin door. The cargo hook allows the Kingfisher to conduct sling load operations up to 4000 pounds (depending on the fuel load) in support of missions requiring external loads. Each of the two cameras provide FLIR, ambient light amplification (similar to current NVGs), and normal day/night synthetic vision to the crewmembers. The first camera is mounted under the nose of the aircraft for the pilots. The second camera is mounted behind the main cabin door to support rescue operations occurring below the aircraft. Both of the cameras are retracted inside the fuselage during non-operation. The Kingfisher is also equipped with over-water survival kits, emergency medical equipment, and parachutes to improve survivability in the event of an emergency.

Integrated in the Kingfisher's mission equipment suite will be a state-of-the art de-icing system. This system will provide control surface and main rotor system de-icing through the use of heated elements. The advanced flight control system already provides hot air through the blade spar and subsequent ducting. This hot air could be used as one element of the hub and main rotor de-ice system.

The Kingfisher will also incorporate emergency floatation devices which, when activated, will allow it to safely stay afloat after a forced sea landing. This system uses large inflatable bladders located under the fuselage, as shown in Figure 9. Augmenting the floatation system are the nacelle and wing floatation kits. Emergency floatation device activation also triggers the emission of emergency beacon signals in the guard frequencies (121.5 and 243.0 MHz) and emergency codes from the aircraft transponder and emergency locator transmitter (ELT).

Figure 9: S-76 Emergency Floatation Device

Table 8 provides a comprehensive listing of the described equipment.

	Item	Quantity	Function	Weight Est. (Each)	Cost Est. (Each)
Commo	Communication Management Sys.	2	UHF/VHF/FM/HF/SATCOM/ ICS/Wireless Voice & Internet	30 lbs	$28,943
	Cabin Commo. Management Sys.	1	UHF/VHF/FM/HF/SATCOM/ ICS/Wireless Voice & Internet	8 lbs	$5,000
Mission Equipment	Multifunction Display (MFD)	4	NAVAID, Radar Altimeter, WX Radar, Search Radar, Storm Scope, Ground Prox., Cockpit Alerting System, SYNVIS, Flight Symbology Flight Instr. & FLIR/D/N Image	20 lbs	$25,000
	Center MFD	2	Digital Mission Map, & Integrated Instrument System	20 lbs	$30,000
	Flight Director Panel	1	Auto Pilot	15 lbs	Not Available
	Flight Management System	2	Mission Data Input, Flight Data Recording, Health & Usage Monitoring Sys, & Video Recording System	10 lbs	$67,604
	Transponder	1	Aircraft Identification	5 lbs	$28,000
	Helmet Integrated Display Sight System	2	FLIR/NVG image, & Flight Symbology	4.4 lbs	$20,000
	Wescam 20TS/QS (Primary - Nose) Wescam 12D (SAR - Belly)	2	Flight NVD/SAR	20TS/QS (240 lbs) 12D (40 lbs)	Not Available
	Pilot Assisted Hover Control (Cabin)	1	Limited Lat/Long Hover Control for Flight Engineer	5 lbs	Not Available
Rescue and Survival Equipment	Breeze-Eastern Model HS-29800 (600 lb Recue Hoist)	1	Retract Rescuees	170 lbs	Not Available
	Breeze-Eastern CH-9000 (Cargo Hook)	1	Sling Load/Resupply	22 lbs	$7,250
	Switlik Life Raft (6 Pax Life Raft)	1	Emergency Floatation Device	135 lbs	Not Available
	Air Method Modular Medical Cabinet (EMS Equipment)	1	Medical Support	70 lbs	$70,000
	Air Method Articulating Patient Loading System	2	Medical Support	26 lbs	$55,000
	LRSE Kit (Survival Kits)	1	Emergency Gear	67 lbs	Not Available
Crew Eq	Mini Softie Parachute	6	Emergency Inflight Egress	14 lbs	$1,345
	Switlik Aviation Vest LPU 21 D/P	4	Crew Floatation Device	3 lbs	Not Available

Table 8: Comprehensive Equipment List[25]

7 FLIGHT CONTROL SYSTEM DESIGN

7.1 Smart Material Overview

Smart materials show tremendous potential for applications in control, vibration reduction, and noise suppression, among many other applications. The most promising of these materials are: shape memory alloys (SMAs); megnetostrictives; and piezoelectrics (PZT).[26] In very general terms, these materials produce a strain (or a stress if blocked) when subjected to a particular source of energy.

Shape memory alloys are materials (metals) which deform when subjected to thermal energy. In other words, when heated, these materials produce displacements relative to some reference point. SMAs produce good strains (on the order of 6%) but have a relatively small maximum operating frequency of about 1 Hz.[27] This low frequency response significantly hinders their potential application for active cyclic control.

Magnetostrictive materials deform when subjected to a magnetic field. The strains produced are somewhat better than piezoelectrics but not as good as SMAs.[28] In order to create the magnetic fields that cause strains, however, magnetostrictive-based actuators require relatively large coils. Since size and weight are critical attributes of an actuator-based control system, these type of materials are not the best candidates.

Piezoelectrics (PZT) are the most promising type of smart material currently being investigated. Piezoelectric materials produce a mechanical strain when an electrical field is applied to them. PZT materials (in stack configurations) are characterized by small strains (on the order of 0.1%) but can produce large block forces. They can operate (i.e., displace) at frequencies as high as 1,000 Hz.[29] They are also relatively unaffected by temperature changes.

Piezoelectric materials can also be configured as bimorph benders. In this arrangement, two "slabs" of piezo material are mounted together with a conducting or insulating material in between (depending on the particular bender design). When an electric field is placed on one slab, a bending moment is created. By simultaneously applying an opposite field on the other slab, an even greater moment is created. Bimorph benders have much greater bending displacements than piezo stacks. Their major limitation, however, is that their block forces are much smaller.

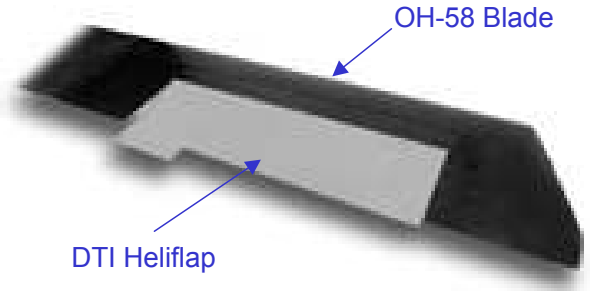
7.2 FCS Tradeoff

7.2.1 Baseline: Heliflap™ Actuation System

For a baseline FCS concept, the Heliflap™ system developed by Diversified Technologies was selected.[30] This compact electromagnetic system is believed to be well suited for secondary Higher Harmonic Control (HHC), as well as for primary flight control in the near future. The actuator has an electric motor, integrated in the blade, that deflects an elevon.

Compared to most smart material driven flap systems, the Heliflap™ is capable of producing forces and displacements on a much larger scale and shows potential for precise, real-time feedback control.

A prototype was built and tested on a full-scale OH-58 rotor. Figure 10 shows the design and some of the specifications. The actuator produces the largest deflections at the lowest power consumption when in resonance. At 81% of the OH-58 rotor speed, elevon deflections of +/-6° at 21 Hz (4.4/rev) are possible.



Heliflap Prototype Specifications	
Frequency Range	0-36 Hz
Possible Deflections	+/- 8 deg.
Torque	50 ft lb
Required Power	200-6,000 W
Length	24 in.
Flap to Blade Chord	46%
Weight	25.2 lb

Figure 10: Heliflap™ Prototype Design and Specifications

This concept's rotor system does not require a tilting swashplate for cyclic control inputs. The simplicity of the individual actuators is also expected to be beneficial. The main drawbacks to this system are its overall complexity as well as its increased weight (in the rotating frame).

7.2.2 Concept One: Electromagnetic Actuation System

One of the blade actuation devices considered for the Kingfisher uses electric power in a dramatically different manner than the Heliflap.™ This concept was proposed initially by Dr. Robert Loewy of the Georgia Institute of Technology. A large permanent magnet fixed on the outer shell of a torque tube is placed around a solenoid that encircles the flexbeam. The magnetic dipole moment of the solenoid is varied by manipulating both the magnitude and the direction of the current fed through the solenoid. In this manner, the size of the torque tube's deflection and its direction can be varied. The electric power required for the actuation does not come from a high-power slipring, but rather from a mast-mounted generator that continuously supplies power to the flight control system. Given enough power, both the cyclic and the collective pitch could be controlled with this actuator. A DC signal would be generated for collective control and an AC signal for cyclic control. Figure 11 shows a three-dimensional rendering of the concept. A shape memory alloy is integrated in the blade spar in order to alter the twist of the blade for flight condition optimization (i.e., helicopter vs. airplane modes). A small slipring, located below the generator, would provide the means for transmitting the pilot's commands into the rotating frame.

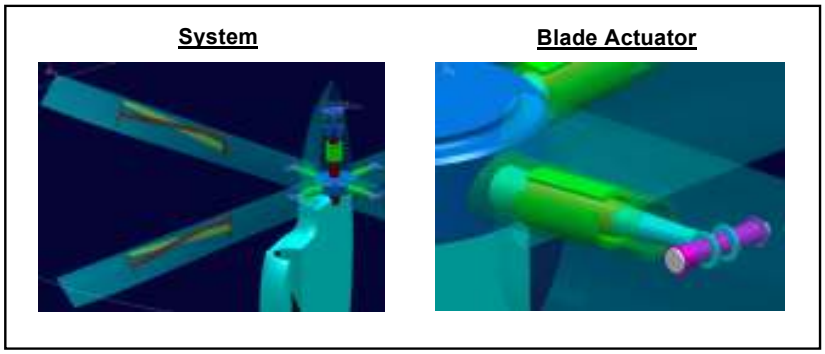


Figure 11: Electromagnetic Actuation Schematics

Although conceptually promising, this actuation arrangement has many technical issues that need to be resolved. For example, the rotor in the generator needs to be spinning at a much faster rate than the rotor itself. A gearbox would have to be integrated into the design. In addition, the power electronics required to handle the high currents and voltages would add a large amount of mass to the rotating frame. Furthermore, the magnets on the torque tube would change its stiffness and some method would have to be devised to accurately analyze the frequency response of the whole system.

7.2.3 Concept Two: Piezo-Pneumatic Flap Actuation System

Modern efforts in the area of piezo-actuated rotor control systems have generally focused on single-stroke actuation techniques. An example is the X-frame actuator, designed by Prechtl and Hall, which uses a mechanical system to amplify the piezo stack's displacement.[31] Although amplified, this displacement is not sufficient to provide cyclic control authority. Piezo stacks can provide tremendous forces (48,000 N block force in the case of the P-247.70 stack produced by Polytech PI Company) but, conversely, produce extremely small displacements (120 μm for the P-247.70 stack).[32] Because of the small displacement, the work that can be produced per cycle is also quite small. However, since piezo actuators can operate at frequencies in the 1,000 Hz range, the work that can be produced per second (i.e., power) is potentially very large. The P-247.70 stack, for example, is capable of producing 1.44 kW of power under optimum conditions.

Another concept considered was a piezo-actuated pneumatic pump system which would be designed to capitalize on this premise. Instead of using single-stroke displacements for each control cycle (e.g., flap displacement), this system would operate at its maximum frequency, store the energy as a compressed gas, and then release the stored energy when needed for flap actuation.

Dr. S. Hanagud and Mr. Patrick Roberts at the Georgia Institute of Technology have designed and manufactured a prototype piezo-actuated pneumatic pump.[33] Although experiments conducted with the pump have yielded promising results (the pump has successfully displaced air and other fluids), this concept is still in the very early stages of

development. Additionally, only extremely limited and crude research has been done to integrate this concept into a cyclic rotor control application. Depicted in Figure 12 is a functional diagram of this system.

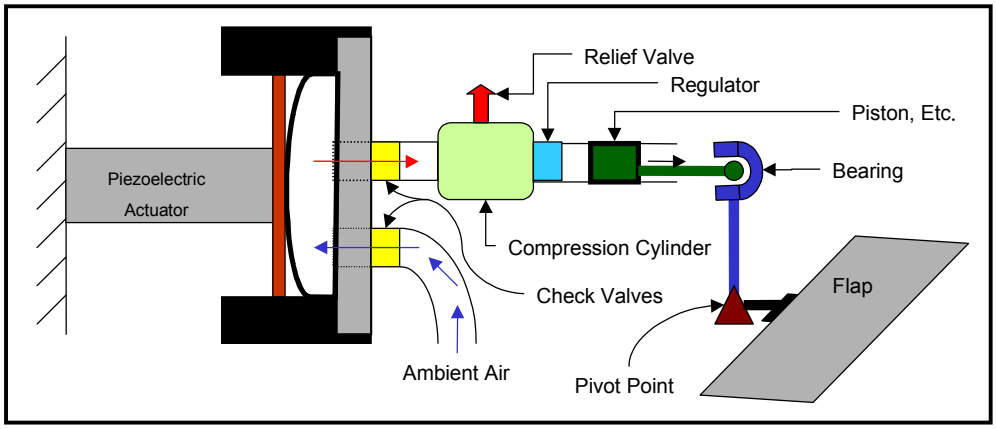


Figure 12: Piezo-Pneumatic Actuation System Functional Diagram

7.2.4 Concept Three: Piezo-Modulated Circulation Control

Dr. Stefan Dancila and Dr. Erian Armanios from the Georgia Institute of Technology have developed CC schemes that use piezoelectric actuators to control the amount and direction of blown air.[34] The blown air (from a slot located near the trailing edge) controls the boundary layer using the Coanda effect as shown in Figure 13.

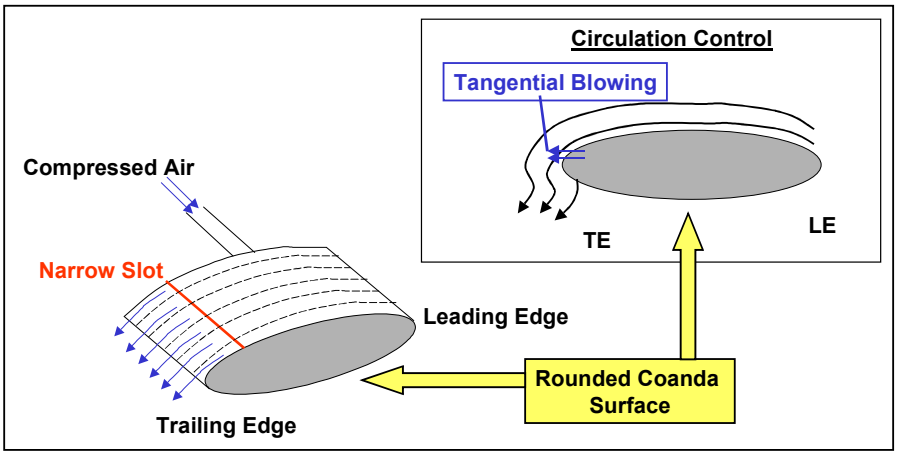


Figure 13: Circulation Control Concepts[35]

As shown in Figure 14, inside the airfoil is a chamber that is connected to the narrow slot in the airfoil surface. The chamber houses a compressed air conduit for supplying and holding compressed air. A passageway connects the conduit to the slot in the upper surface of the airfoil. The lower wall of the passage has a slit allowing a shutter to move selectively into the passage and obstruct the flow of compressed air through the passageway. The shutter is attached to a piezoelectric bimorph bender. By applying a voltage to the bender, the airflow out of the slot in the airfoil surface may be modulated.

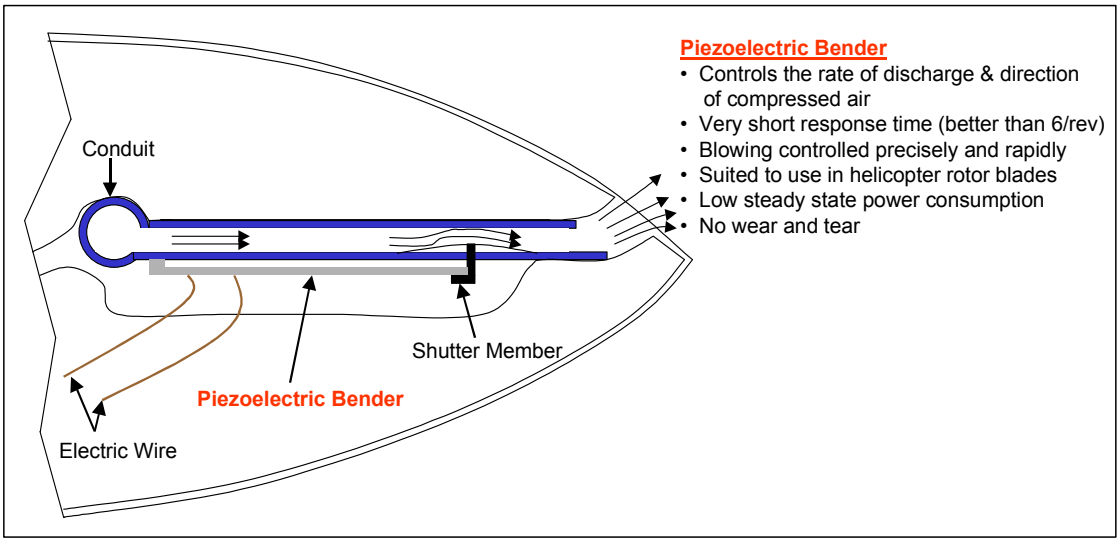


Figure 14: Circulation Control Using Piezoelectric Actuator[36]

The use of the piezoelectric bending actuators significantly increases the capability of CC. The frequency response of the system, a major problem of past CC efforts, becomes virtual instantaneous.

7.2.5 FCS Comparison and Selection

A Pugh Matrix (Table 9) was used to evaluate the alternative concepts and to determine the best FCS for this application. The electric blade root actuator, the piezo-pneumatic energy storage system, and the piezo-modulated circulation control concepts were compared to the Heliflap™ baseline concept in three main categories: performance; feasibility; and cost.

The electric blade root actuator is an innovative method of applying known electromagnetic and SMA technologies. Its positive characteristics include improved drag performance as well as increased hover effectiveness. On the other hand, this concept's technology readiness level (TRL) and its system complexity were considered to be worse than the other FCS concepts.

The piezo-pneumatic system is also an innovative application of current technology. If successfully developed, this system would overcome the most significant limitation of piezo stacks – extremely small stroke length. However, the pump structure itself is still in the early stages of development and virtually no work has been done to integrate the pump into a flap-actuation mechanism. The system would also suffer drag penalties.

Pugh Matrix Civil Search and Rescue Tiltrotor			Alternative Concepts			
			BASELINE Heliflap Elevon	1 Electric Blade Root Actuator	2 Piezo-Pneumatic System	3 PZT Modulated CC
AFFORDABILITY	Performance	Frequency Response	DATUM CONCEPT	-1	-1	1
		Induced Drag		1	0	1
		Profile Drag		1	0	1
		Cruise Effectiveness		1	0	-1
		Hover Effectiveness		0	0	1
		Control Authority		1	0	1
	Feasibility	Scaleability		0	1	0
		Weight		-1	0	0
		TRL		-1	0	1
	Costs	Total System Complexity		-1	0	0
		RDTE		-1	0	0
		Operation		-1	0	0
		Reliability		0	-1	-1
			Σ + 1	**4**	**1**	**6**
			Σ - 1	**6**	**2**	**2**
			Σ 0	**3**	**10**	**5**

Table 9: FCS Pugh Matrix

The piezo-modulated CC concept was determined to be the most feasible of the concepts considered. In terms of performance, the CC is an extremely effective way of achieving high values of C_l. This type of system can also reduce noise, improve airfoil stall characteristics, and enhance efficiency. By incorporating piezo-modulation, CC airfoils can provide the control authority and frequency response necessary to eliminate the need for the cyclic swashplate.

7.3 Circulation Control Overview

The CC concept is based on the Coanda effect.[37] In the early 1950's, Kaman and Yuan used an elliptical airfoil with a mechanical flap under the trailing edge for a helicopter rotor blade. In wind tunnel tests, Kaman and Yuan obtained a lift coefficient as high as 7.3. [38]

For a CC airfoil, a tangential jet sheet flows over the curved trailing edge surface of the aft portion of the airfoil. The jet remains attached to that curved surface because of a balance between the sub-ambient pressure in the jet sheet and the centrifugal force around the curvature. At very low blowing, this jet prevents aft flow separation and thus provides very effective boundary layer control. Applying CC on a circular cylinder provides the highest lift characteristics. However, cylinders provide poor drag characteristics during forward flight. Therefore, thinner blown elliptical airfoils were developed. The CC canard elliptic airfoil with 20% thickness obtained a lift coefficient as high as 6.8.

Using a CC elliptic airfoil is feasible for helicopter mode. However, drag penalties will be incurred when the CC elliptic airfoil rotors are used in airplane mode. Mr. Liu, Dr. Sankar, Mr. Englar and Dr. Auja at the Georgia Institute of Technology have studied a supercritical airfoil with a 30-degree dual-radius CC wing flap. The highest lift coefficient

achieved was approximately 3.3 at 4 degrees angle of attack. The same supercritical airfoil achieved a lift coefficient of 1.2 at 10 degrees angle of attack with no blowing.

7.4 Flight Control System Configuration Design

7.4.1 Power Required

Nomenclature Used in Analysis[39]

A_{jet}	Area of Jet Slot	S	Area of the Blown Lifting Surface
C_l	Lift Coefficient	V_{oo}	Free Stream Velocity
C_d	Drag Coefficient	V_{jet}	Blowing Jet Velocity
C_μ	Momentum Coefficient	ρ_{oo}	Free Stream Density
$\dot{m}$	Mass Flow Rate of Blowing Jet	ρ_{jet}	Jet Density

In order to determine the feasibility and begin to develop the FCS hardware layout, preliminary power requirement calculations were conducted. By using the stability and control program EVMCEP, a series of trim solutions were obtained. The initial goal was to determine which flight condition required the most cyclic control power. Based on analysis using this program, the critical flight condition was determined to be sideward flight. The RFP required a capability to hover in 30 knots +/- 15 knots crosswind condition. This requires an equivalent sideward flight capability of 45 knots. To be conservative and for robustness, the vehicle was designed for a sideward flight capability of 60 knots. EVMCEP yielded a trim condition which required 755 lbs of cyclic control force per rotor for this flight condition.

A blade element/momentum theory performance simulation spreadsheet was developed in order to analyze the performance of the rotor system. This spreadsheet modeled the rotor system with and without circulation control blowing. Blown airfoil data, in the form of an airfoil chart, was obtained using a two-dimensional CFD model.[40] Elements of lift and drag, using this data, were of the form defined by Equation 1 and Equation 2, respectively (the CFD model gave values for the a's and the δ's).

$$C_l = a_0 + a_1 C_\mu + a_2 C_\mu^{\,2}$$

Equation 1: Lift Coefficient

$$C_d = \delta_0 + \delta_1 C_\mu + \delta_2 C_\mu^{\,2}$$

Equation 2: Drag Coefficient

The momentum coefficient, which appears in the lift and drag equations, is defined by Equation 3.

$$C_\mu = \frac{V_{jet}\dot{m}}{S\frac{1}{2}\rho_\infty V_\infty^{\,2}} \qquad \text{where:} \qquad \dot{m} = \rho_{jet} A_{jet} V_{jet}$$

Equation 3: Momentum Coefficient

The vehicle was modeled at hover (using the BEM spreadsheet) with non-blown airfoils to obtain the value for θ_o. The blown airfoil was then added to the simulation and C_μ was iterated until the vehicle produced 755 lbs of thrust per rotor beyond the previous thrust produced by the non-blown airfoil. This condition yielded a C_μ value of 0.025 and represents the upper limit of control power required.

In order to solve for the mass flow rate (and total flow slot area), certain flow parameters had to be assumed. The jet pressure and temperature were assumed to be 40 psi and 200ºC, respectively. These conditions were selected because they represent typical values of engine compressor (or APU) discharge pressures and temperatures. These parameters will invariably change depending on engine power setting and ambient conditions so these factors would have to be included in flow scheduling. The engines were selected as the primary source for compressed air. The APU serves as the backup source.

The jet speed was assumed to be 0.9 Mach (for the given flow density at maximum cyclic power). This value was assumed for a number of reasons. By remaining in the subsonic range, noise emissions will be reduced and ducting/slot erosion will be kept to a minimum. Additionally, the flow will not become choked during the transition from subsonic to supersonic speeds.

With these assumptions, the area of the jet (using the above equations) was calculated to be 0.02477 ft^2. This area corresponds to a slot length and height of approximately 7 feet and 1.08 mm, respectively. The 7 feet length corresponds to one-half of the rotor radius. With this length, each blade would be slotted on the outer half of the blade length. By blowing at the outer half of the blade, control power will be maximized (i.e., a greater moment will be created by increasing lifting forces on the outer area of the blade). Blowing over the inner portion of the blade radius, besides creating less control moments, will also likely be less effective because the airfoil is optimized for forward flight and so has tremendous twist near the root. Therefore, the outer half-radius of each blade was selected as the region which will provide the best performance.

The slot height of 1.08 mm represents an effort to optimize this critical dimension among several considerations. A small slot height would increase problems associated with debris blockage of the slot. This blockage could degrade performance and could significantly reduce the control authority of the affected blade. A larger slot height would cause the blade to have poorer structural performance (i.e., a larger hole per cord-wise cross-section has less material and is less structurally sound). Larger height also removes airfoil lifting surface area from a given section of blade. With these considerations, the 7 foot by 1 mm slot per blade represents a good starting point from which the geometry can be further optimized for a given jet area.

With these geometry and flow conditions, the mass flow rate was calculated to be 0.1323 slugs per second or 256 ppm. Equation 4 was used to calculate the blowing power required.

$$P = \frac{1}{2}\dot{m}V_{jet}^{\ 2} = \frac{1}{2}\rho_{jet}A_{jet}V_{jet}^{\ 3}$$

Equation 4: Blowing Power

This calculation resulted in a power requirement of 199 HP per rotor (although the calculation is per blade, effectively only one blade per rotor is providing cyclic lift at a given moment). This represents the cyclic control power required at the previously defined maximum power flight condition – 60 knot sideward flight. This does not at all represent steady-state or normal cyclic control power requirements. Figure 15 depicts the power requirements for sideward flight from 0 to 60 knots.

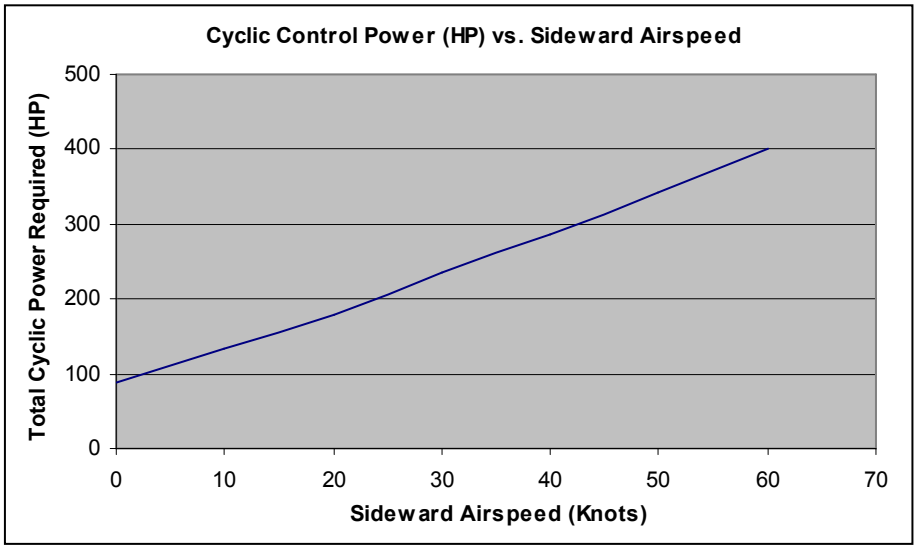


Figure 15: Circulation Control Power Required

The power requirement chart depicted above was based on the forces resulting from the trim solutions obtained by EVMCEP. These forces were applied to the method described above in order to determine the power required at varying airspeeds.

The Kingfisher, as designed, has adequate power available for sideward flight at 60 knots. At maximum gross weight, the Kingfisher requires 2,670 HP to hover at 95ºF. With 4,250 HP available, it has over 1,500 excess horsepower. Any excess beyond 400 HP, however, could not be used for more cyclic control authority since the jet area and flow parameters are fixed. With one engine inoperative, however, the Kingfisher has less excess power. Under this scenario (at full useful load and 60% fuel), the Kingfisher requires 2,464 HP to hover. For two minutes, the Kingfisher can produce 2,656 HP, which is adequate power to maintain 20 knots of sideward flight (the RFP does not stipulate a crosswind

requirement under OEI but, obviously, an appropriate level of control authority is a must). During these two minutes, the APU could be started, which would add about 200 HP worth of equivalent control authority (about 35 knots of crosswind) to the FCS. These control margins are adequate when one considers that only a minimum amount of cyclic control authority is required for forward flight in helicopter mode. In fact, the excess power available with OEI would allow the vehicle to travel forward at a rate of 70 knots in helicopter mode. With these capabilities in mind, the Kingfisher could easily survive an OEI condition simply by turning into the wind, developing forward airspeed, and transitioning to airplane mode as it normally would.

The power calculations described above are somewhat crude and represent preliminary data. Several considerations make these calculations more conservative than they will likely be. The power required for the vehicle does not account for the power reductions resulting from the simplified flight control system. For example, with the advanced FCS, smaller hydraulic pumps (and less plumbing, structural support, etc.) would be required, which would save power. Also, less FCS mass (due to the simplified mechanical structure) would result in less power required. Additionally, adequate cyclic power is already included in the VASCOMP program sizing (i.e., an amount of power is required for cyclic control with traditional swashplates; the cost savings resulting from the elimination of this power requirement is not included in the calculations). Therefore, the Kingfisher will likely require less than 2,464 HP to hover with OEI and so the excess power will be greater than stated.

7.4.2 Configuration Design

The goal of this stage of the preliminary design is to determine the best physical construct of the FCS (i.e., on-blade components). Specifically, the ducting arrangements as well as the ideal number and arrangements of the bimorph benders must be determined.

For the Kingfisher, eight benders per blade were selected. This number was selected for several reasons. Bimorph benders are extremely reliable and have no moving parts (other than the material itself) so a large amount of redundancy is not necessary. With eight benders, an adequate amount of redundancy is provided and maximum control authority, per blade, would only be reduced by 12.5% given a single bender failure. Each bender will have to overcome frictional forces within the ducting. These forces will be larger, relative to the total bender power, if a large number of small benders are selected rather than a few moderately sized ones. Fewer benders requires less wiring, less complex ducting, and fewer communication signals from the fixed to rotating frames. These reasons combine to suggest that eight is a good number of benders per blade.

The bender characteristics are listed in Table 10. These values were obtained by scaling existing benders produced by Physic Instrument, GmbH.[41] The scaling was done using non-linear, fundamental properties of bimorph benders rather than simple linear scaling.

Piezoelectric Bender Characteristics			
Length	15.0 cm	Voltage	0 to 60 V
Width	8.89 cm	Temp. Range	-20 to +80°C
Thickness	1.44 mm	Max Travel	3 mm
Weight	164 g	Block Force	5.34 N

Table 10: Piezoelectric Bender Characteristics

As stated previously, the engines and/or APU will supply the compressed air. A bleed air manifold (used also for cockpit/cabin heat and engine start) will connect both engines and the APU. A bleed air duct will be connected to the rotor hub of each rotor. The compressed air will enter the hollow tube of the hub shaft and then enter each blade through a pneumatic slipring.

Figure 16 (foldout, pg. 38) depicts the on-blade flight control configuration. The compressed air will travel through the titanium blade spar and then divide into eight secondary ducts. These ducts lead to chambers housing the shutters which are moved by the bimorph benders. The shutters open and close to modulate the flow. A flexible membrane provides the interface between the shutter and the chamber inner wall surface. The duct geometry requires bender displacements of 3 mm. From these chambers, the ducts each lead to one of eight ten-inch slots in the rear of the blade.

By maintaining constant spar pressures, the bimorph benders can quickly release an amount of air mass necessary for control, as dictated by the controller. The benders can operate at frequencies significantly greater than those required for cyclic control (the Kingfisher rotor operates at about 7.5 Hz). To avoid control coupling, the vehicle will blow air at a mean value and then deviate from that mean to create differential lift (cyclic control) for each rotor. CC blowing will be gradually washed out during transition and is not used in airplane mode.

A small hub-mounted processor (HMP) will be mounted on each rotor hub (in the rotating frame). Each HMP will contain four identical individual processors. Each of these processors will send and receive independently routed signals (for redundancy) and will serve as the single point through which piezo bender command signals will pass (as given by the main AFCS computer). It will also receive health signals (e.g., circuit continuity) from the benders which will be transmitted back to the AFCS computer (which is mounted in the fixed frame).

Figure 16: Flight Control System Design (foldout)

The use of the HMP allows for dramatic future system performance upgrades. As the CC flow dynamics and interactions become better understood, the HMP capability can also be improved. By precisely managing the CC flow, noise emissions, vibration problems, and other performance characteristics can be improved. An example of a potential software-driven (i.e., HMP) performance improvement is the use of pulsed air jets rather than continuous ones. By using high frequency pulsed jets, the incremental lift coefficient (ΔC_l) can be increased significantly.[42] This improvement could be incorporated after the fundamental FCS had been certified and could be accomplished by software modifications only.

Mounted in the vicinity of the blade root will be a flow shutoff valve (one per blade). This will allow the flow to be completely removed from any individual blade (for example, in case of a cracked spar leading to uncontrolled flow loss). In the event of a single blade failure (flow stoppage), one blade's cyclic thrust will be lost (recall, the collective is mechanical). However, with a rigid, gimbaled rotor, this type of failure will not result in a loss of vehicle control or in a catastrophic increase in vibrations. The blades will fly in the same plane and the thrust vector can still be tilted with the authority of the remaining blades. The flow to the blade opposite the failed blade may have to be shut off as well in order to avoid thrust vector procession.

By using the arrangement described above, seven cross-frame (i.e., fixed to rotating and back) signals are required. Individual blades will share some signal paths. Two redundant control signals, from the AFCS computer to the HMPs, command the appropriate bimorph bender deflections for flow modulation (each HMP directs the motion of all eight benders within its blade). Two redundant shutoff valve channels allow the AFCS computer to bypass the HMPs and shut off the flow to individual blades. A health monitoring signal channel (the redundant signal is incorporated in the control signals) allows the HMPs to report the blade system health to the AFCS computer. Finally, two redundant power channels provide electricity to the rotating frame components. A high-power slipring is not required since all rotating-frame components operate at low power levels.

7.5 Stability & Control Augmentation System (SCAS)

The fly-by-wire design of the Kingfisher FCS allows for highly effective flight control methods. The aircraft will feature an advanced stability and control augmentation system (SCAS) using recent adaptive technologies in stability augmentation and flight limit detection/avoidance. The main function of the system is to provide static and dynamic stability in all parts of the flight regime which will result in a significant reduction in pilot workload. The goal is to have an augmentation system which can satisfy the handling requirements as described in the ADS-33D standard.[43] Mission-related features include precision hover, limited authority cabin hover control in helicopter mode, and trajectory following autopilot for automated search patterns in airplane mode. Figure 17 shows an overview of the proposed concept.

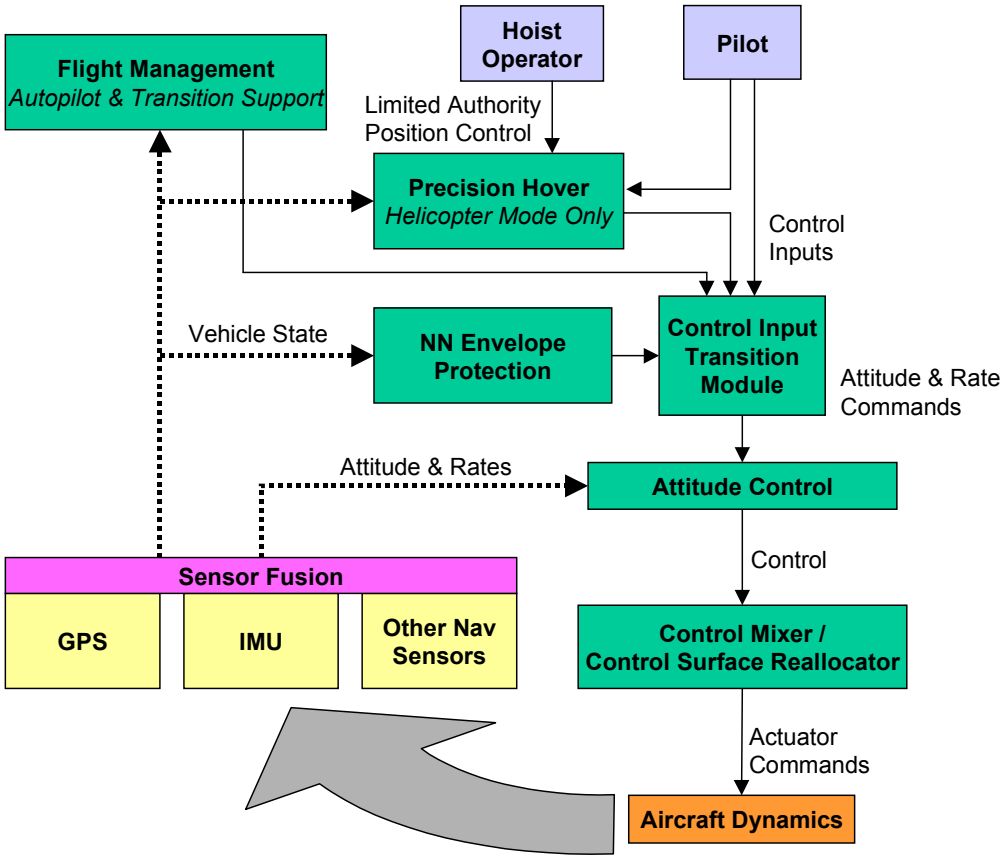


Figure 17: SCAS Loop

7.5.1 Desired System Responses

The Kingfisher SCAS uses a model following control approach. A proper selection of the desired system response types for all flight modes is essential. A summary of the chosen augmentation methods is shown in Table 11. During a rescue mission, the pilot faces a high workload while maneuvering the aircraft over the rescue site. The required handling characteristics in hover mode are provided by attitude control hold (ACAH) augmentation, which can be supplemented by a position hold mode using position and velocity data from the navigation sensors. In airplane mode, the aircraft requires a rate-based response type for the roll channel (rate command attitude hold, RCAH). Directional Stability/Direction Hold with Rate Response (RCDH) is used for the yaw channel in helicopter mode.

CHANNEL	MODE	
	Airplane	Helicopter
Pitch	ACAH	ACAH
Roll	RCAH	ACAH
Yaw	RCAH & Turn Coordination	RCDH

Table 11: Control Augmentation Methods

7.5.2 Precision Hover

During hover, the pilot can engage a precision hover module to reduce his workload. This is implemented as an outer loop using the attitude control system and navigation/position data as shown in Figure 18. The aircraft cabin is also equipped with a limited authority hover control stick. It allows the hoist operator to position the aircraft above the target.

This system will have very limited control authority (10% beyond pilot trim position) and could be overridden/disengaged by the pilot at any time.

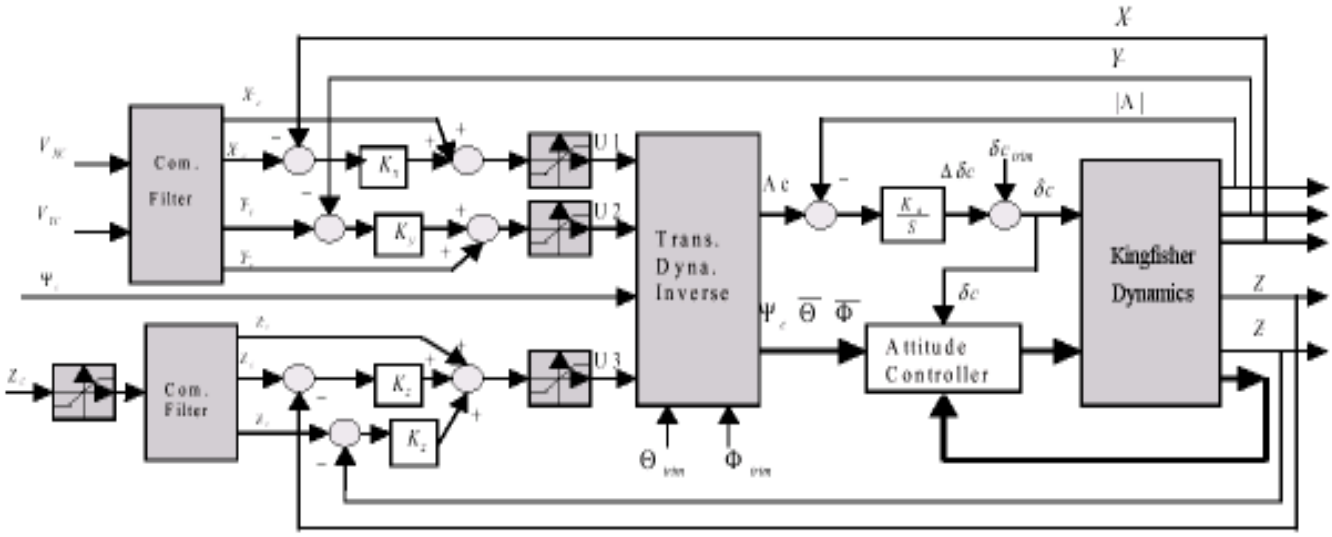


Figure 18: Precision Hover Outer Loop

7.5.3 Flight Management Computer

In order to automate some pilot tasks, a flight management software component is added to the AFCS computer. One of its purposes is to provide autopilot functions in airplane mode, including a trajectory controller for preprogrammed flight paths. Navigation sensor feedback, such as a Global Positioning System (GPS), is used to steer the airplane on a pilot-programmed course. A set of predefined search patterns can be used and modified by the flight crew in order to achieve optimal coverage of a rescue site. This is extremely beneficial when performing a rescue mission in an area with poor visual cues such as deserts or open sea. Additionally, the flight management software surveys and supports the transition between airplane and helicopter mode by adjusting proper nacelle angles, flap positions and rotor settings. The pilot can then concentrate on flying the aircraft and does not have to worry about these adjustments.

7.5.4 Required Sensors

The selected control functions generally require a full state feedback of the vehicle movement. This includes position, velocity, attitude and attitude rates. Modern GPS aided inertial navigation systems can provide that information easily with great accuracy. An extended Kalman filter is then used to fuse noisy sensor information into a consolidated state vector.

7.5.5 Why Adaptive Control

Conventional control system design is usually based on a gain scheduling approach. In order to select the correct gains for all operating points in the aircraft's flight envelope, high fidelity simulation or flight tests have to be conducted.

Additionally, very little data about the dynamics of the innovative rotor control system of the Kingfisher is currently available. This uncertainty makes it more difficult to use a traditional gain-scheduling method.

Recent research involving adaptive control strategies provides an ideal solution to these obstacles.[44] The Kingfisher therefore features an adaptive neural net controller in the attitude control loop. A sample block diagram for the ACAH setup is shown in Figure 19.

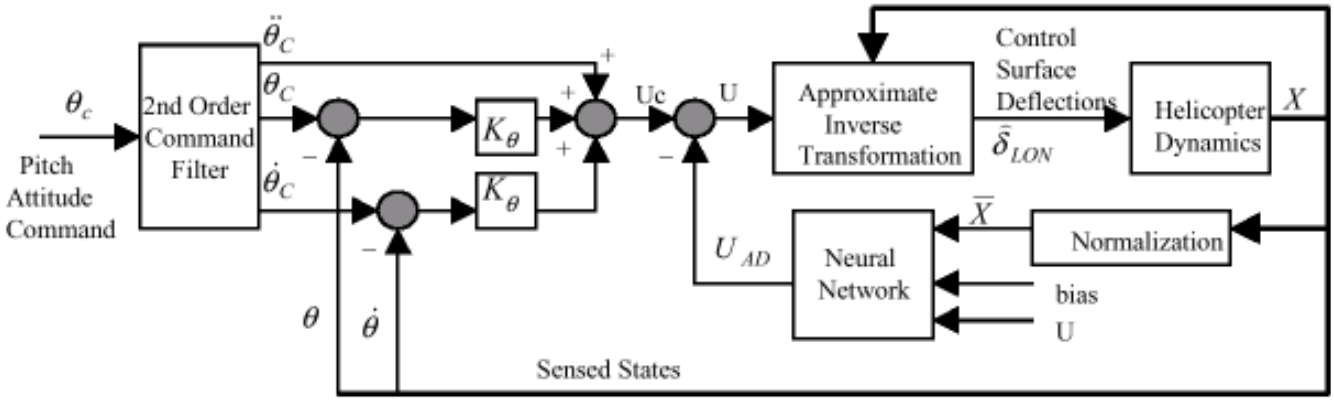


Figure 19: ACAH Control Loop (Pitch Axis Depicted)

The controller tries to track the ideal system response of a second order system using feedback linearization. The neural network block, using a full state feedback of the aircraft, will correct the error resulting from the approximate inverse transformation.

Note that a linear hover model is used for the inversion in all flight states, including airplane mode. The desired handling qualities in cruise flight can be maintained as the neural network adapts to the changing flight condition. ADS-33D handling requirements can be achieved by adjusting the command filter parameters and the linear controller gains. A similar setup is used for the RCAH configuration.

7.5.6 Simulation of the Attitude Control Loop

Figure 20 depicts the stability roots of the Kingfisher in hover without the SCAS, showing that the aircraft has unstable oscillatory modes in both the pitch and roll channels.

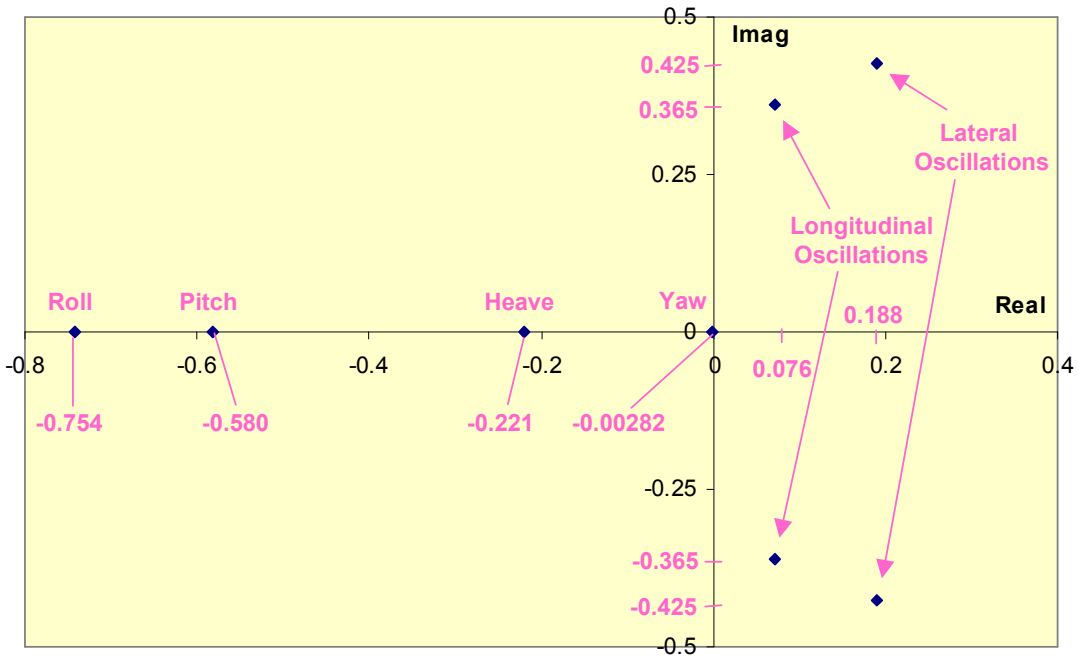


Figure 20: Open Loop Stability Roots (Hover)

In order to show that the selected attitude control system stabilizes the aircraft and fulfills the handling quality requirements, an ACAH control loop was modeled using the SIMULINK module in MATLAB.

Aerodynamic stability and control derivatives computed by EVMCEP have been used to create a simple linearized aircraft model for several operating points. The feedback linearization part of the control loop is optimized for hover. This method provides a simple way to test the controller design, without having to implement a full-featured simulation model for a tiltrotor.

The ADS-33D requirements for ACAH are: to achieve pitch attitudes of -30º and +10º in less than 1.4 seconds from hover flight; to ensure that the pitch attitude angle returns to +/- 10% of the peak excursion in less than 10 seconds following a pulse input; and, that a step pitch command shall produce a proportional pitch change within 6 seconds. Level 1 handling qualities will be achieved when the aircraft dynamics have a bandwidth of $\omega_n = 2.5$ radians and a damping ratio of $\zeta = 0.8$.

The results from the sample simulation iterations reflect perfect model tracking, highlighting the capabilities of this control architecture. The step and pulse response plots for the pitch channel at hover are depicted in Figure 21.

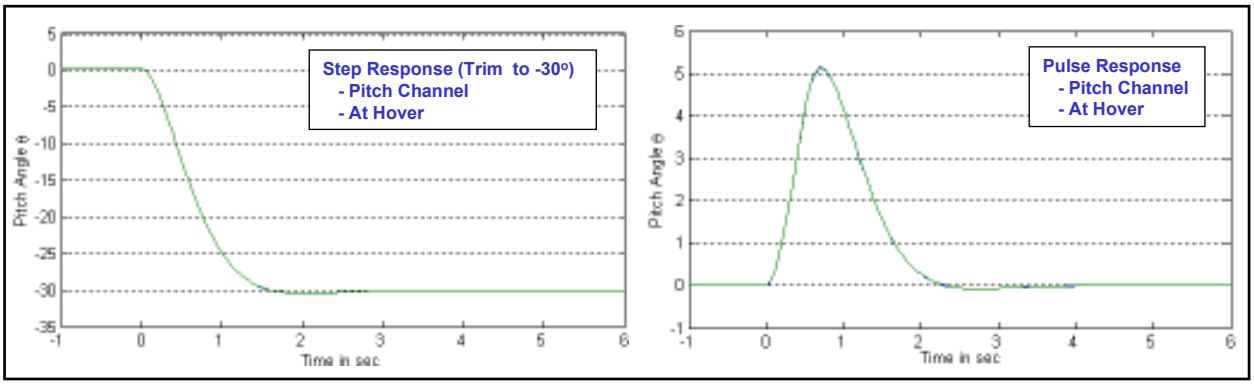


Figure 21: Step and Pulse Response Plots, Pitch Channel (Hover)

7.5.7 Limit Detection and Avoidance System

The Kingfisher, as with of any other aircraft, has a set of flight envelope limits which must not be exceeded. These limits include, for example, speed limitations (due to stall and other effects), maneuver limitations (due to structural damage/failure potential), and, in helicopter mode, vertical descent rate (due to asymmetric vortex ring state). A limit protection system helps to keep the aircraft from exceeding its flight envelope.

Since the limits change with different aircraft states, a limit prediction system is needed. This can be achieved by using off-line trained neural networks that predict the limit parameters based on some of the vehicle states and control inputs.[45] The limit parameters are then translated into control margin estimations which are used to cue the pilot through the use of a force feel feedback on the control sticks. Figure 22 shows a block diagram of such a mechanism.

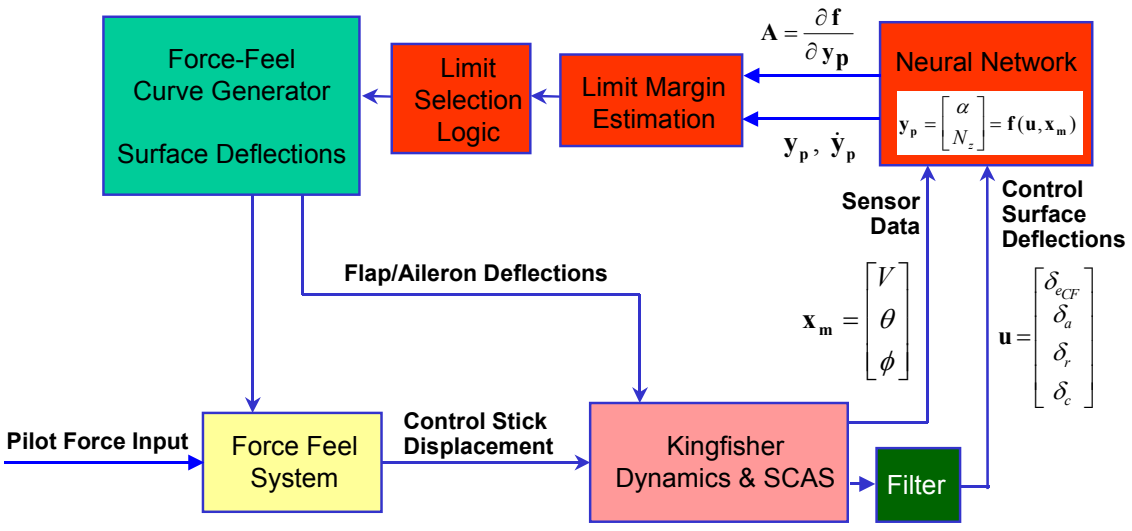


Figure 22: Limit detection and avoidance system

Certain limits will be avoided automatically through the flight control system. For example, when a tiltrotor is entering an asymmetric vortex ring state (through excessive helicopter-mode vertical descent), its lateral stability and

controllability decays significantly, putting the aircraft in a dangerous flight condition. After detecting the onset of the condition (by comparing, for example, actual roll rate to predicted roll rate), the AFCS would manipulate other control surfaces such as flaps or ailerons in order to stabilize the aircraft. Such a system will enhance the Kingfisher maneuverability considerably, extending the flight envelope beyond that of current tiltrotors.

7.6 FCS Subsystem Tradeoffs

7.6.1 Flight Control System Interface

The goal of this tradeoff study was to determine the best means by which pilot inputs would be transmitted to the vehicle control surfaces. Three different types of systems were considered. They are, from least to most technically complex, hydromechanical, electrical (fly-by-wire), and optical (fly-by-light). Hydromechanical systems have, typically, been the method used for transmitting pilot input into flight control movements. These systems are heavier and more mechanically complex than the other two systems.

Electrical fly-by-wire systems have recently gained acceptance and are used in many flight vehicles. These systems eliminate the need for mechanical linkages (push-pull tubes, torque shafts, etc.) from the cockpit control sticks to the flight control servos (or other actuation systems) and so reduce the system weight, number of components, and the amount of required maintenance. Also, the fly-by-wire system allows for a greater degree of interface between the control surfaces and an active flight control computer.

Also considered was a fiber-optic based fly-by-light system. Fiber-optic cables are capable of transmitting significantly more information than comparably sized electrical wire bundles. This system would use several fiber-optic cables (for redundancy) to transmit pilot control input signals to actuators in the rotor system. The major disadvantage is that this technology is still unproven, especially with respect to the necessary interface. The risks of employing such a new and potentially expensive technology were determined to outweigh the advantages in weight savings and in increased information-carrying capacity.

Based on the metrics of cost and reliability, the fly-by-wire concept was selected as the best system for this application. A proven means of data transmission, it offers good performance at a good price.

7.6.2 Rotor Hub Design

Two types of hubs were considered for the Kingfisher - either a gimbaled or a bearingless rotor hub. Also considered was the number of blades per rotor. Current tiltrotor designs (the V-22 and the BA-609) use three-bladed gimbaled rotor systems. Bearingless rotor systems are increasingly being used in industry for helicopter applications. These rotors are less mechanically complex and so require significantly less maintenance than teetering or fully articulated

systems. They are, however, more difficult to design because of the challenging aspects of flexure design. The gimbaled design offers proven reliability and allows for the elimination of lead-lag dampers. Another advantage to the gimbaled arrangement is that it reduces the problems associated with single-blade CC failures (as discussed previously). For these reasons, a gimbaled hub was selected.

Regarding the number of blades per rotor, the Kingfisher will use four blades instead of three (as used by existing tiltrotor aircraft). By using four blades, the chord width of each blade can be decreased (hence decreasing the profile drag) for a given solidity. Other benefits include improved propulsive efficiency, decreased noise emissions, and decreased individual blade loading.

7.6.3 System Communications – Fixed to Rotating Frame

One of the challenges of this design is to determine the method by which information is to be transmitted from the non-rotating to the rotating frame of reference. Traditional systems use a swashplate to "transmit" control signals from the fixed to the rotating frame. With individual blade control, however, an alternate method must be devised.

Two unique concepts for information transmission were considered: a traditional slipring arrangement as well as a "wireless" system using radio frequency transmissions. In the "wireless" system, transmitters in the fixed and rotating frames would transmit information to receivers in the opposite frame. This type of system has not been used in any existing rotorcraft (though it is being considered for the Army RASCAL testbed) and so the technology is still undeveloped. An additional drawback with this arrangement is that it could potentially cause EMI problems with other system components (such as navigation equipment). Further, external electromagnetic emission sources (such as ship radars) could affect the vehicle's fixed-to-rotating communications and hence disrupt or disable the control system. Because of these potentially large problems with the wireless RF system, the traditional slipring arrangement was selected for the Kingfisher.

7.7 Future Research Required (Technological Problem Areas)

7.7.1 Bimorph Bender Dynamics

With the rotor spinning at 100% RPM, tremendous forces act on the bimorph benders. The outermost bender of each blade is subjected to about 427 lbs of centrifugal force. Additional forces include friction forces due to the chamber-bender interface, friction and static forces of the compressed air, and inertial forces caused by bender motion. These forces combine to create a very complex dynamic system. Future research is required to optimize the bender locations and quantities for this environment. These problems can be mitigated through detailed design changes. For example, if inertial forces cause too great a delay in response, one can increase the number of benders and decrease the bender travel distance.

If the centrifugal forces create problems, one could move the benders inboard and adjust the duct geometry to deep the modulated flow at the outer half of the blade.

7.7.2 Flow Dynamics

Although the circulation control concept is simple, the flow dynamics will be extremely complex. The mass flow rate and jet velocity (which have direct effects on C_μ and hence lift), will be functions of a large number of independent variables. These variables include: compressor discharge temperature and pressure (which depend on engine conditions such as power setting and engine health); free air temperature (which affects heat transfer rate); and pressure altitude (which affects ρ_{oo}). All of these variables combine to create a very complex flow condition. Adding to the flow complexity is the fact that there are an infinite number of control positions (each bender has a continuous range of positions from fully closed to fully open).

Future research is required to model the flow in terms of all of these factors. Although the flow is complex in analysis, the basic conceptual design allows for tremendous future improvements in flow tailoring, and therefore improvements in performance. With individual blade processors, software-only upgrades would dramatically improve flow characteristics. The inclusion of neural network adaptive control also helps to mitigate flow dynamic problems.

7.7.3 Control Authority During Autorotation

Since the vehicle uses compressed air for cyclic control authority, a source must be available to maintain that authority. With a dual engine failure in airplane mode, full vehicle control (including autorotative touchdown) would remain. In this scenario, the pilot (or aircraft) would have adequate time to start the APU (about 7-10 seconds is required with current APUs) prior to entering autorotation (the vehicle does not use circulation control in airplane mode).[46] The APU would then provide the compressed air for cyclic control.

In low altitude hover, however, dual engine failures become more critical. In these situations, normal APU start times may be too slow to provide the pilot adequate time to recover. Future research is required to overcome this problem. One possibility is to develop an extremely fast starting APU. This may or may not be feasible. A more practical solution would be to eliminate the APU (use electric engine starters) and include in the design one or more clutched, electrical-powered emergency compressors. The conceptual design relies on an operational solution to this problem – the APU must be on during low altitude hover conditions.

7.7.4 Rotor State Sensors

Because the design uses gimbaled hubs, the number of possible rotor states is kept to a minimum (lead-lag variation, for example, is essentially eliminated). The possible rotor state variables include: blade azimuthal position (which

is measured by azimuthal position sensors); rotor speed (also measured by the azimuthal position sensors); feathering pitch angle (which is easily measured because of the mechanical nature of the collective system); and the rotor teetering angle (not measured in the conceptual design). Of the states listed, only the teetering angle remains directly unmeasured. However, by measuring the vehicle attitude and angular rates, one can likely infer the thrust vector orientation and hence the teetering angle. The problem with this method is that there will be a phase lag between the thrust vector tilt and the aircraft response. If this lag causes control problems, the vehicle will have to incorporate a direct method of measuring the teetering angle. Although relatively easy to integrate into the hub design (a simple potentiometer at the hub pivot point would measure the teetering angle which, combined with blade azimuthal position, would indicate thrust vector orientation), future research would be required to determine if this sensor is essential.

8 AIRFOIL DESIGN

Proper airfoil selection is essential in optimizing the vehicle's performance in the various modes of flight. Conventional helicopters have a large amount of data on CC applications. However, no tiltrotor CC airfoil data is available; therefore, the CC concept was applied to the XV-15 rotor blade. Table 12 shows the XV-15 section airfoils of the XV-15 rotor blade.

r/R	% Thickness	Section
0	0.28	64-(5.7)27A
0.5	0.18	64118A
0.75	0.12	64-(1.5)12A
1	0.08	64.208A

Table 12: XV-15 Airfoil Sections[47]

Two-dimensional computational fluid dynamics (CFD) analysis was performed at the 0.75 r/R blade location to determine the effectiveness of the CC application. This location, as a representative sample, was selected because CC blowing is required from about 0.5 to 0.98 r/R of the rotor blade. Since CFD data for a CC supercritical airfoil was available at the Georgia Institute of Technology, the NACA 64-012 airfoil was modified by adding the aft section of the CC supercritical airfoil at 89 to 100% of the chord line. Figure 23 shows the CFD body-fitted grid and the stream function contour for the NACA 64-012 airfoil at 0º angle of attack. This airfoil has a modified trailing edge with a blowing slot to maximize the benefits of the Coanda effect. To obtain the C_l, C_d, and C_m values, Mr. Naveen Gopal at the Georgia Institute of Technology used the following parameters: Mach number of 0.291, Reynolds number of 1.5×10^6, and C_μ of 0.04.

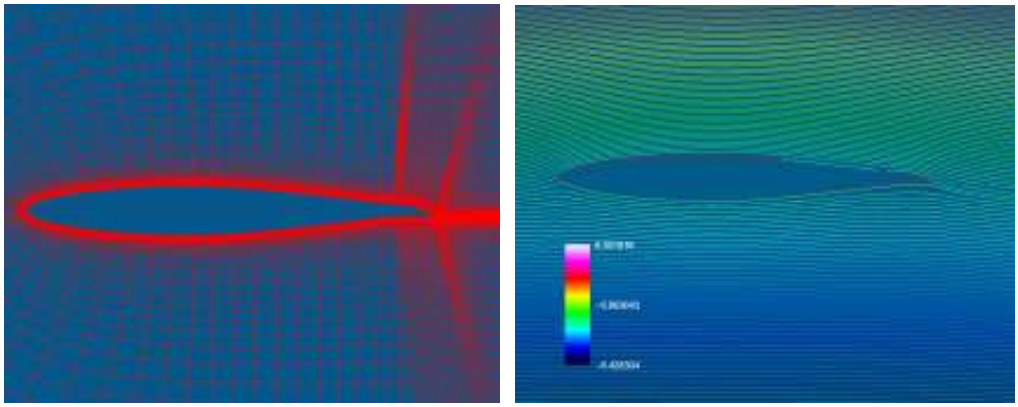


Figure 23: NACA 64-012 CC Airfoil w/ 0° Flap

CC airfoils have obtained higher C_l values than conventional high-lift systems. At Georgia Tech, a supercritical CC airfoil with a 30° fixed flap at 0° angle of attack obtained C_l values greater than 3 for $C_\mu = 0.1657$.[48] For the modified CC NACA 64-012 airfoil at 0° angle of attack with 0° fixed flap, the following values were obtained: $C_l = 0.774$, $C_d = 0.021$, and $C_m = -0.374$. The following values were obtained for 2° angle of attack with 0° fixed flap: $C_l = 1.076$, $C_d = 0.035$, and $C_m = -0.472$. These values are significantly greater those produced by conventional airfoils. A typical conventional airfoil does not obtain a C_l value of 0.7 until approximately 5º angle of attack with 0º flap.[49]

Since blowing is required only during helicopter and conversion flight modes, the XV-15 blade twist distribution was optimized for airplane flight mode at cruise airspeed using Equation 5.

$$\theta_{tw} = \mathrm{ATAN}\left[\frac{V}{\Omega\left(\frac{r}{R}\right)R}\right]$$

Equation 5: Linear Twist Rate

As shown in Figure 24, two linear twist distributions were determined (by linear regression) from root to midpoint and midpoint to tip of the blade. The twist distribution was then applied, along with other rotor attributes, to a blade element/momentum theory (BEM) spreadsheet to determine performance characteristics of the rotor system.

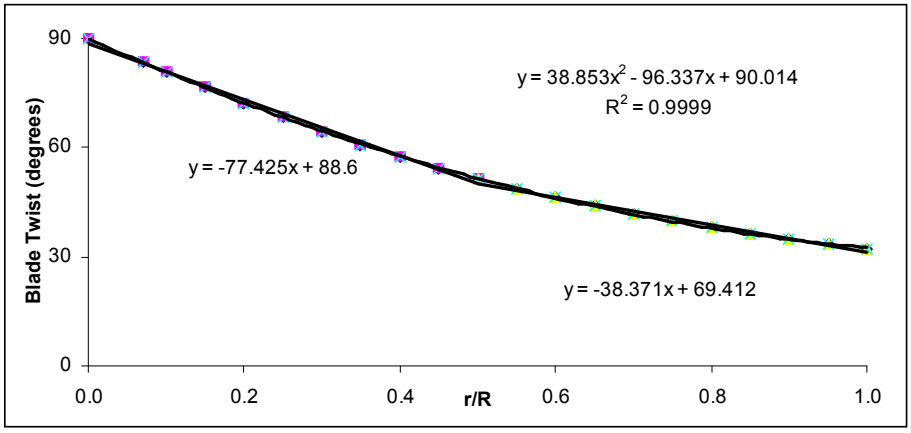


Figure 24: Airfoil Twist Distribution

9 STRUCTURAL DESIGN

9.1 Structures Overview

The structural design and analysis of the Kingfisher is primarily affected by factors such as static loading, fatigue loading, emergency situations, and environmental concerns. The Kingfisher's static loading requirements are based on the placement of the major components and the flight loading.

The aircraft's fatigue loading requirements are determined based on the expected flight loading and the overall number of cycles during normal mission conditions. The fatigue loading conditions also contribute to the determination of component replacement time and inspection intervals.

The primary failure modes, for static and dynamic load analysis, are measured by energy absorption. The Kingfisher is designed with a composite structure to provide the optimum balance between material weight and material static strength/fatigue resistance.

Emergency situation considerations must be integral to the design of the Kingfisher. These situations can result in a wide range of outcomes – from minor to catastrophic. The structural design of the Kingfisher must be as resilient to these situations as possible. The over-water nature of the Kingfisher's mission envelope also adds a level of complexity to emergency considerations.

Environmental concerns such as ultraviolet rays, heat, moisture, and solvent damage are alleviated through structural treatments. Because composites are to be used, a thin metallic foil strip must be built into the composite lay-up for lightning strike prevention.

9.2 Airframe Description

Figure 25 (foldout, pg. 51) depicts the Kingfisher's airframe structure. This is a semi-monocoque design consisting of graphite and nomex honeycomb bulkheads, stressed honeycomb sandwich skin panels, graphite/epoxy beams, stringers, longerons, spars, ribs, and frames. Blades are made of Kevlar 49/Epoxy. The beams along the underbelly of the aircraft must provide adequate structural rigidity to meet crashworthiness requirements.

This vehicle has also been designed with enough skin thickness to avoid excessive stress levels, deflections, strains, and buckling. The goals of the detailed structural design are to reduce the stress concentrations, fretting corrosion, hidden undetectable cracks, and the probability of a single failure causing a component failure.

Figure 25: Structural Cutaway (foldout)

9.3 Velocity-Load (V-n) Diagrams

The velocity-load (V-n) diagrams calculated for this vehicle show that it meets structural design criteria as prescribed in Subpart C of FAR 25, 29, and XX. Figure 26 and Figure 27 show the flight limit load factors and airspeed of the Kingfisher in helicopter and airplane modes, respectively.

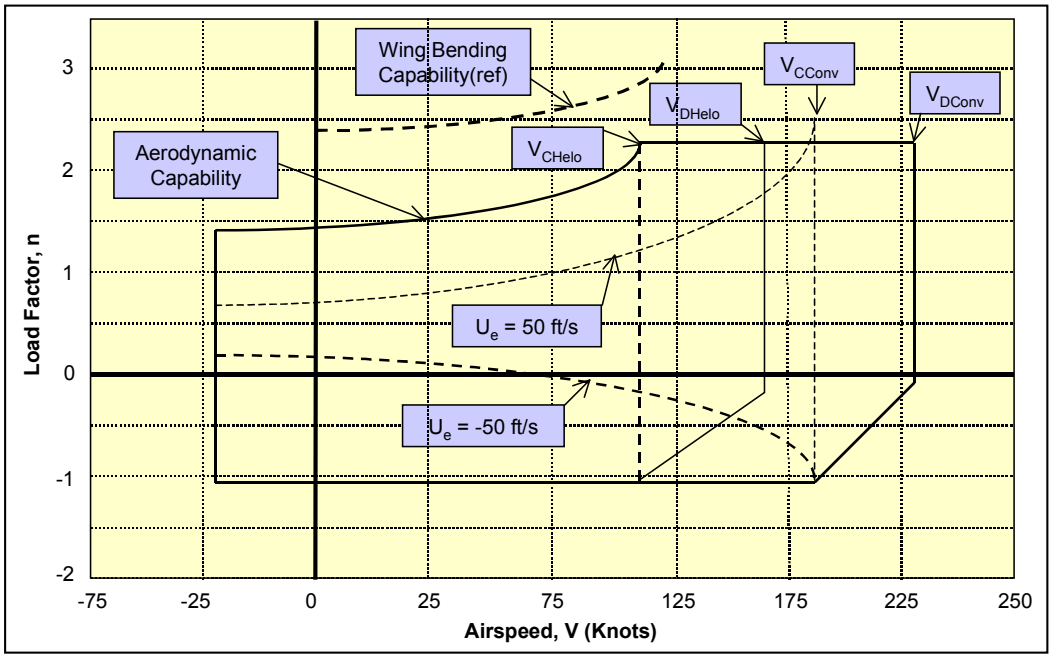


Figure 26: V-n Diagram (Helicopter Mode)

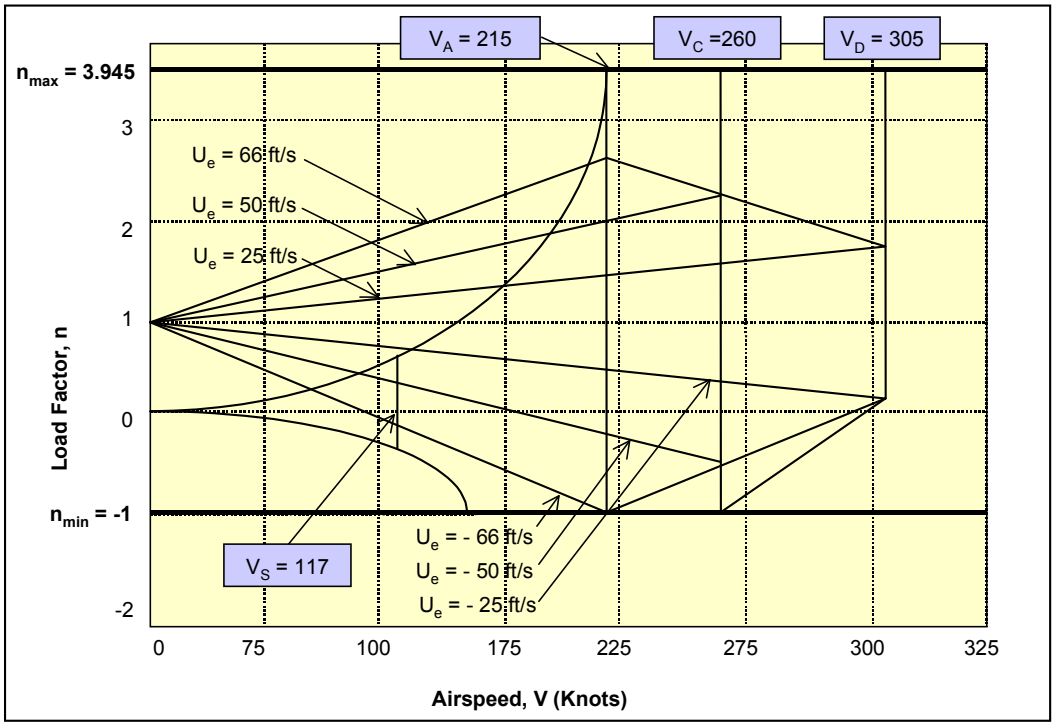


Figure 27: V-n Diagram (Airplane Mode)

9.4 Aeroelastic and Blade Analysis

Proprotor instability is one of the major limitations in the design and operation of a tiltrotor aircraft. Tiltrotors generally exhibit proprotor instability in the fundamental wing bending modes during high-speed airplane mode of flight.[50] Wing tailoring is one method used to mitigate proprotor instability. For this vehicle design, the wing has been stiffened to minimize the mast pitch motion that aggravates proprotor stability.

The computer program DYMORE was used to analyze the aeroelastic effects on the Kingfisher. DYMORE is a state of the art, multi-body, non-linear dynamics code.[51] It facilitates the analysis of the rotor system's structural integrity, elastic deflection magnitude, aeroelastic stability, aerodynamic loads, and blade natural frequencies.

The fan plot in Figure 28 shows the blade frequencies for the gimbaled hub configuration. Blade characteristics were based on XV-15 composite blade data as well as VASCOMP generated information. Also included was analysis performed by Alexander and Smith during their study of composite tiltrotor blade design.[52] By modeling the entire gimbal, we were able to show the motion of the complete hub instead of observing only one blade in a traditional fan plot. We observed 20 separate modes for this system (up to 4 per rev). The torsional frequencies occur much higher than 4-per-rev and so are not shown.

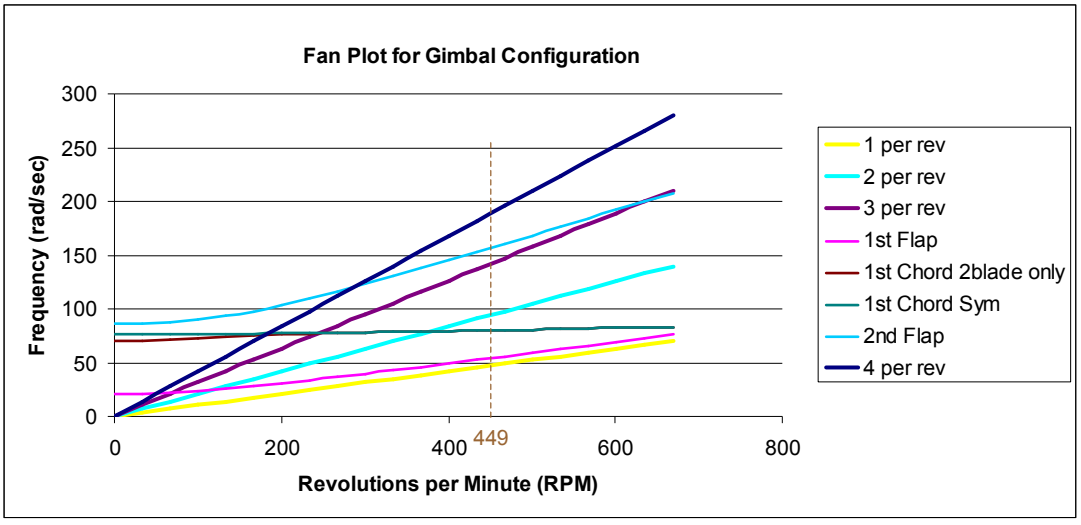


Figure 28: Fan Plot (Gimbal Configuration)

9.5 Weight and Balance

Major component weights and balances are shown in Table 13. Component weights were calculated with VASCOMP.

Component	Weight (lbs)	x_i (in)	y_i (in)	z_i (in)
Engines	816	144.00	54.00	0.00
Fuselage	1,904	262.5	43.50	0.00
Wing	1,015	155.00	68.00	0.00
Nacelles	305	144.00	64.00	0.00
Horizontal Tail	151	458.00	155.00	0.00
Vertical Tail	164	416.00	109.00	0.00
Landing Gear (Main)	460	207.00	10.00	0.00
Landing Gear (Nose)	230	50.00	9.00	0.00
Flight Controls	1,355	37.00	31.00	0.00
Hydraulics/Electrical	519	80.00	84.00	0.00
Instruments	286	37.00	31.00	0.00
Air Conditioning/De-Icing	303	260.00	32.00	0.00
Personal Accomodations	423	205.00	33.00	21.00
Rotor System	983	144.00	116.00	0.00
Drive System	1,365	128.00	75.00	0.00
Fuel System	345	155.00	68.00	0.00
Engine Access	269	144.00	64.00	0.00
Avionics	343	37.00	15.00	0.00

Empty Weight	11,234
Fixed Useful Load	1,269
Operating Empty Weight	12,503
Payload	1,213
Fuel Weight	3,333
Aircraft Gross Weight	**17,049**

Measurement	X_{cg} (in)	Y_{cg} (in)	Z_{cg} (in)
Aircraft Center of Gravity (Airplane Mode)	151.04	1.7321	56.92
Aircraft Center of Gravity (Hover Mode)	157.13	1.7321	59.65

Aerodynamic Center of Aircraft (Hover)	Xac = 174.70
Aerodynamic Center of Aircraft (Airplane)	Xac = 169.65
Aicraft Static Margin	Xac - Xcg = 17.57

Table 13: Weight and Balance Statement

The aircraft's center of gravity (CG) was determined using the aircraft's CATIA model, which included weights and locations of all major components. Figure 29 shows the vehicle forward and aft CG limitations based on the vehicle's load distribution.

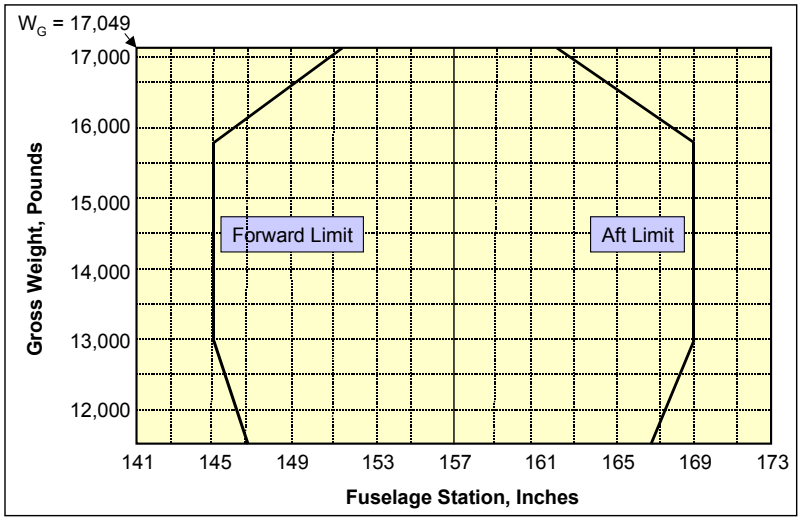


Figure 29: Center of Gravity Limits

9.6 Damage Tolerance and Fatigue Life Analysis

Damage tolerance assessment is a procedure that determines whether specific airframe cracks are minor, and can be monitored through inspection, or if they are major, and can lead to catastrophic failure.[53] Because composite materials exhibit non-linear stress-strain characteristics leading up to a failure, these materials are much less tolerant to overloading.

Although the use of composites makes the fatigue analysis complex, these materials exhibit good resistance to tension fatigue and are less susceptible to local de-laminations that could eventually grow into larger problems.

The Kingfisher is subjected to fatigue loading during all flight modes (helicopter, conversion, airplane). Aircraft fatigue loads are caused by the cyclic changes in loads during both ground and air operations. The cyclic fatigue loads for the Kingfisher have been designed to remain below the fatigue endurance limit during normal flight conditions. Figure 30 shows the vehicle's maneuver and gust load limitations.

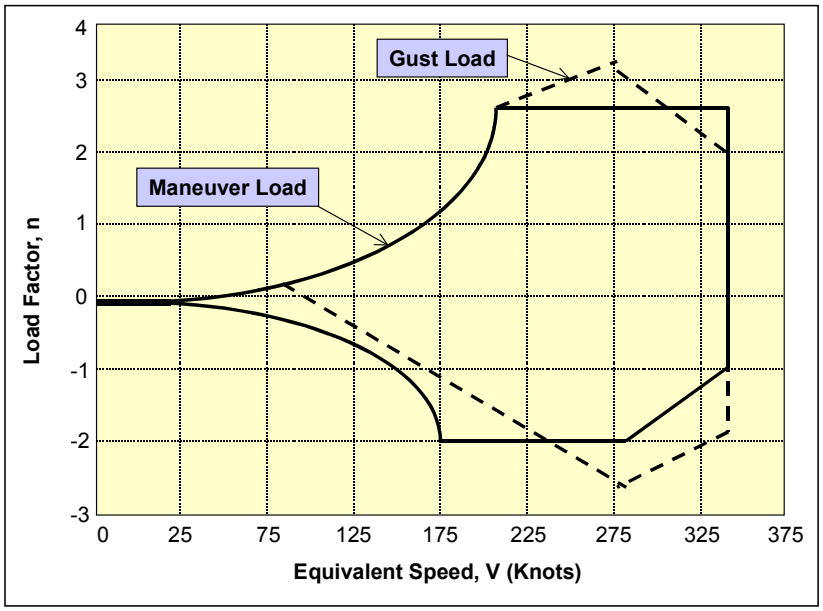


Figure 30: Maneuver/Gust Load Limitation

Component fatigue requirements can be categorized into safe-life, fail-safe, or damage tolerant elements. Safe-life components are designed to be capable of operating for up to 400% of their designed lives. Fail-safe components must be capable of surviving one full inspection interval after the failure of a single element. Fail-safe loads are distributed over alternate load paths in the result of failure. Fail-safe parts are essential in reducing/eliminating the likelihood of catastrophic airframe failure. Most fail-safe parts are used in components such as floor spars, landing gears, load frames, wing stringers, fuselage stringers, and wing load frames.[54] The fail-safe parts are designed to initially fail on the visible surfaces. Regular inspections of these parts will help to identify potential failure modes.

Safe-life parts are evaluated and assigned a specific number or flight hours before they are replaced.[55] Safe-life parts are included on the vehicle's non-redundant systems such as the pressure hull panels, engine support structures, passenger and crew seating, hydraulic systems, electrical and control systems, and flap actuators.

Fatigue load failures can also occur. These occur because of sonic vibrations in helicopter mode and are extremely damaging around high stress locations such as holes and joints. Composite materials provide excellent resistance to acoustical fatigue because of their high damping characteristics.

9.7 Emergency Situations and Crashworthiness

The crashworthy design characteristics for a tiltrotor require a systems approach, with the landing gear, fuselage, and seats functioning together to absorb the vehicle's kinetic energy and slow the occupants to rest without serious injury.[56] Energy absorbing features and large mass absorption occur because the engines and proprotors are located at the end of the wing structure away from occupied areas. Breakaway bolts are installed along the wing roots to allow the wing to fail upon impact and dislocate from the fuselage in a controlled manner.

The Kingfisher provides for rollover strength and strong support structure for restraint of hazardous large masses and seats. The landing gear folds rearward to prevent cabin penetration in the event of a crash. The Kingfisher's crew seating provides fixed load energy absorbers with 12-17 inches of vertical seat stroke.[57] The forward fuselage of the Kingfisher features an anti-plowing design, as well as design features to absorb longitudinal impact forces. The vehicle's under-floor is designed to absorb kinetic energy through a series of crumple zones during vertical impact. Since a crash is rarely exactly vertical, a 30-degree tilt to the vehicle (in all three axes) was considered. The vertical impact velocity for the Kingfisher is about 26 ft per second, as described in FAR Part 25, 29, and XX, for a 95th percentile survivable crash.

The Kingfisher has reinforced hulls to prevent emergency hatches from jamming upon impact and energy absorbing landing gears that allow plastic deformations before fracture. The primary floor has crushable kevlar/epoxy sandwich structures to absorb energy while compacting during impact.

9.8 Materials

A combination of composite materials and metal alloys was selected for this aircraft. Most metals tend to be isotropic (having structural properties the same in all directions), while composite materials tend to be anisotropic (a single ply, having a very high strength and stiffness in the axial direction, but marginal properties in the cross-wise direction). Cross-plying the composite materials based on function and loads enable them to meet and surpass the properties of metals.

Composites possess several other advantages compared to metals. For instance, they are lightweight, easily tailored to meet the design needs, and present a high resistance to fatigue damage. While the disadvantages of composite

materials such as cost, ease of inspection, and location of material defects are important factors to consider, they do not outweigh the benefits. Initially, the cost of using composite materials will be high. However, over the life cycle of the aircraft, cost will be reduced through increased fuel efficiency, increased resistance to corrosion, and decreased maintenance. Composite materials were mainly used in the design of the airframe and interior, while metal was used on the landing gears. Metal gives the landing gears the maximum stiffness at minimum cost. This aircraft's landing gears will be made from 7075 aluminum. This type of aluminum is commonly used because it exhibits a combination of high strength and resistance to stress corrosion.

The most common methods for producing composite components are cocuring and filament winding. Cocuring is defined as curing a composite laminate and simultaneously bonding it to some other surface during the same cure cycle.[58] Cocuring reduces the assemblies and fasteners used on the airframe. Filament winding is an automated process in which a continuous filament strand or tape is treated with resin and wound on a removable mandrel in a prescribed pattern. This method is used to manufacture the flooring, empennage, minor bulkheads, stringer panels, and frames. These minor structure components will be constructed with AS4 Graphite/Epoxy. This material is known for its excellent open hole and material properties, in addition to its relatively low cost. AS6 Graphite/Epoxy will be used for major structure components such as the wing box structure, spar caps, major bulkheads, and airframe skin because of its high strain capability. The wing box structure and spar caps are typically manufactured by filament winding, while the major bulkheads and airframe skin are normally cocured.

The proprotor blades will be made of cocured Kevlar 49/Epoxy. This material is known for its toughness, impact resistance, lower weight, and lower cost compared to graphite. Kevlar also presents excellent damping qualities that reduce flutter and sonic fatigue problems. The aircraft's interior structures are made of mainly low cost thermoplastics. These materials are easily manufactured through thermoforming and stamping.

10 PERFORMANCE RESULTS

10.1 Flight Performance

The Kingfisher's tiltrotor configuration gives increased performance characteristics for SAR missions. Its maximum speed and service ceiling are far greater than a conventional helicopter. In addition, the low-drag airframe and the performance of the PT6C-KF engine (please see Section 11, Engine Selection and Characteristics) give the Kingfisher good speed and cruise performance. Maximum speed and out of ground effect (OGE) hover performance were calculated at standard atmospheric conditions. OGE hover was assumed to require 10% more power than in ground effect (IGE) hover. The OGE Hover ceiling was calculated to be 14,140 feet. At sea level, maximum airspeed and stall airspeed in airplane mode were calculated to be 310 knots and 110 knots, respectively. Maximum endurance was calculated to be five hours.

In airplane mode, the Kingfisher can climb at greater than 4,140 feet per minute (fpm) at the maximum gross weight of 17,049 pounds. It can also climb at 1,022 fpm with OEI. The Kingfisher meets FAR Part 25 Section 25 climb requirements for two engines operating as well as for OEI. FAR Part 25 states that the steady climb may not be less than 3.2% with all the engines operating and 2.4% at OEI during takeoff with landing gear retracted.[59] Rates of climb in airplane mode are shown in Figure 31.

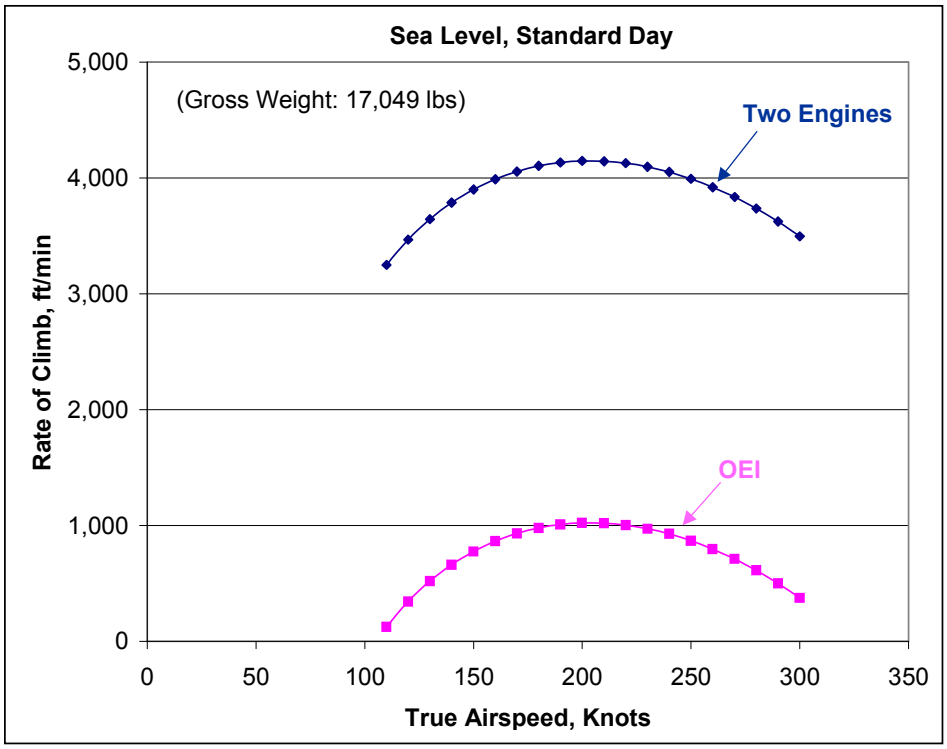


Figure 31: **Maximum Rate of Climb (Airplane Mode)**

At sea level, the autorotative rate of descent was calculated to be 3,871 ft/min at the maximum gross weight. This is a manageable descent rate and allows for a survivable emergency landing. Figure 32 shows that the lighter the aircraft, the faster its autorotative rate of descent. Although counterintuitive, performance tests confirm this rule of thumb (the lighter aircraft has lower potential energy and must come down faster).[60]

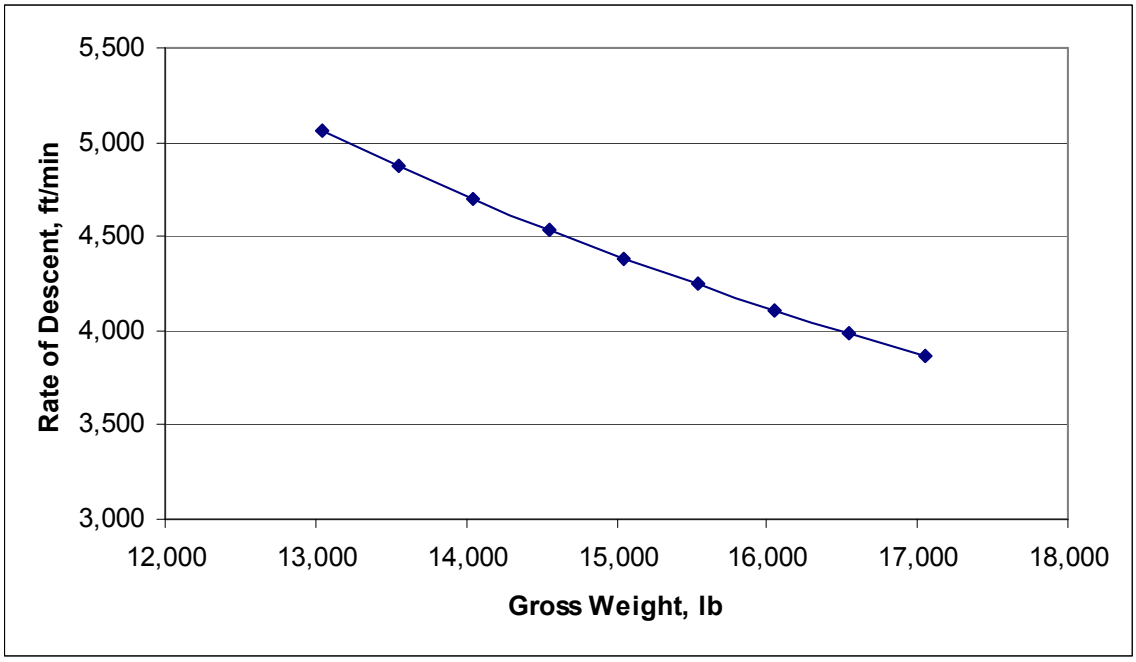


Figure 32: Autorotative Rate of Descent (75 knots)

The Kingfisher's authorized flight envelope is designed in accordance with the FAR Parts 25, 29, and XX performance requirements for the aircraft gross weight. It has greater than standard rate turn (3º per second) capability at its cruise speed of 260 knots.

10.2 Static and Dynamic Stability

Trim conditions were calculated using EVMCEP. Figure 33 shows the trim condition for forward flight in helicopter mode at 500 feet. Trim control inputs in level flight vary smoothly throughout the speed range up to 100 knots. The directional changes in collective and longitudinal stick positions from 40 to 80 knots are probably caused by the rotor slipstream moving onto the horizontal stabilizer.

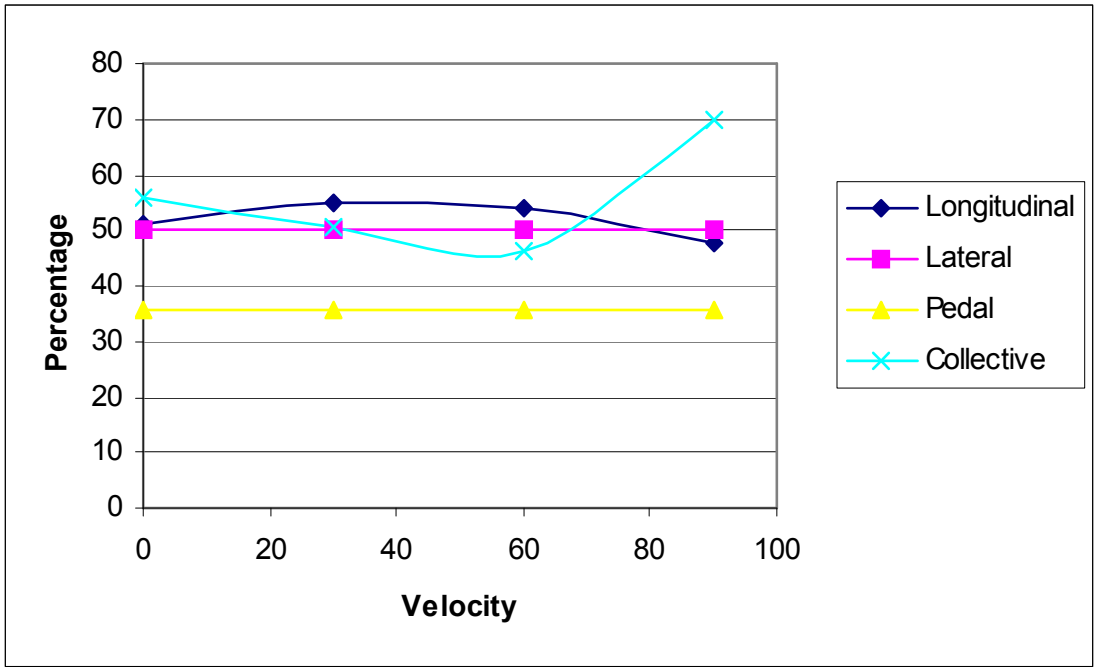


Figure 33: Trim Condition for Forward flight (Helicopter Mode)

Figure 34 shows the Kingfisher's longitudinal, lateral, pedal, and collective travel during sideward flight from 0 to 60 knots at 500 feet. Except for lateral cyclic adjustment, this trim plot indicates that, at a hover, the aircraft will require only moderate control inputs when challenged by strong sideward wind gusts. The RFP requires OGE hover in 30 knots crosswind with 15 knots gust.

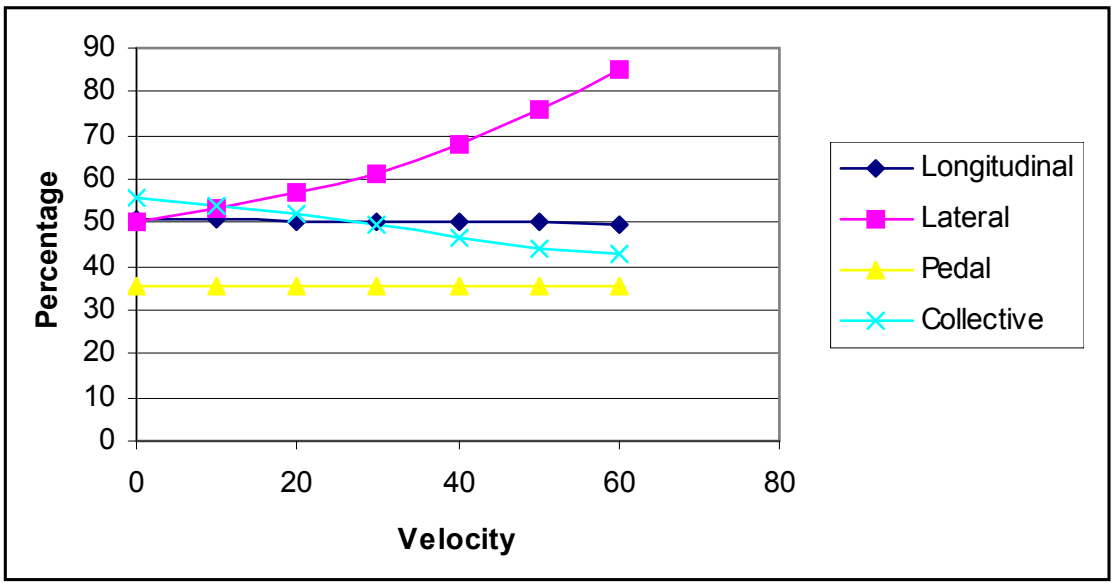


Figure 34: Trim Condition for Sideward Flight (Helicopter Mode)

Figure 35 shows the trim condition for the conversion mode between 0 and 100 knots at nacelle angles of 0 to 30 degrees. In EVMCEP, the helicopter mode is when the nacelle angle is at 0º. The longitudinal trim indicates that the

nacelle angle changes have little impact on longitudinal stick movement from 80 to 100 knots (typical conversion airspeeds). Lateral and pedal trim conditions demonstrate consistent trim patterns in helicopter and conversion modes. The collective trim condition shows the same results for different nacelle angles.

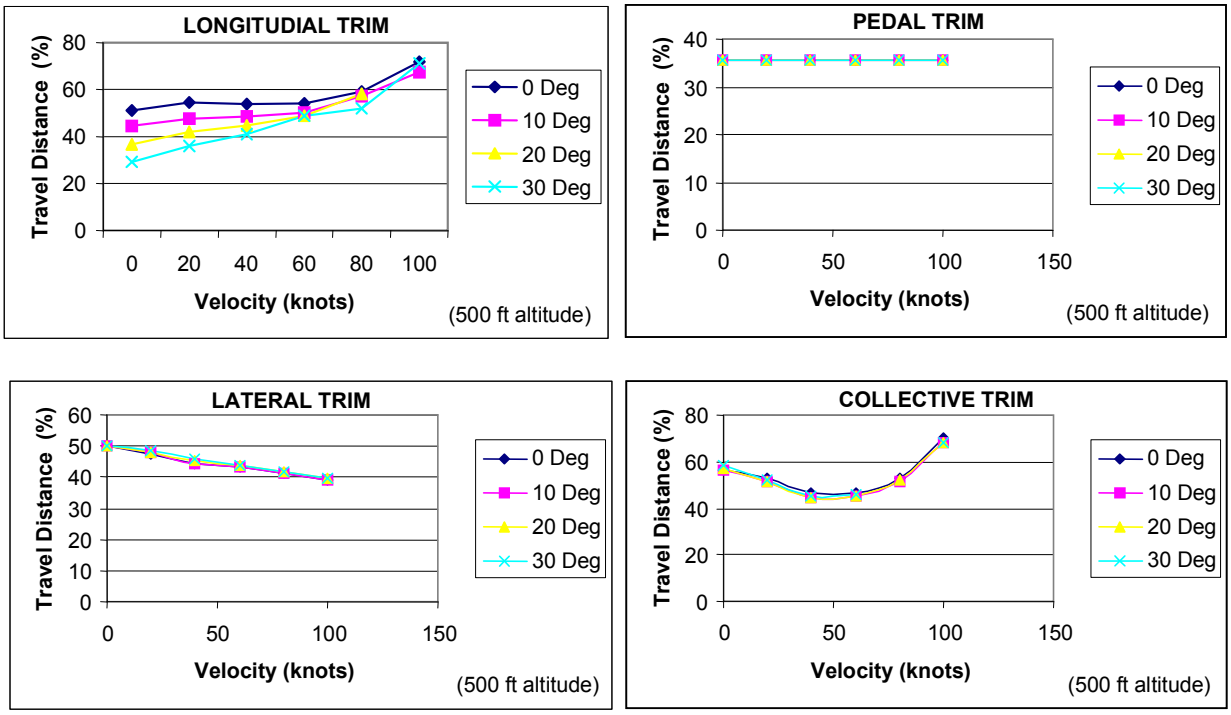


Figure 35: Trim Conditions for Conversion

11 ENGINE SELECTION AND CHARACTERISTICS

11.1 Power Output and Related Assumptions

The baseline engine for the Kingfisher is the Pratt & Whitney Canada (P&WC) PT6C-67A, which is currently undergoing the certification process for use in the BA-609 tiltrotor. The 67A has a maximum continuous power (MCP) rating of 1,940 HP and a One Engine Inoperative (OEI) rating of 2,492 HP.[61] The Kingfisher will incorporate a derivative of the PT6C-67A (designated as the PT6C-KF in this proposal), which will be designed with Integrated High-Performance Turbine Engine Technology (IHPTET). IHPTET will provide a 25% reduction in SFC and a 40% improvement in power-to-weight ratio.[62] Based on VASCOMP analysis, the PT6C-KF will have an MCP rating of 2,125 HP and an OEI rating of 2,656 HP. Although the Kingfisher installed power is greater than the required power, this is prudent at this early design stage. The excess power is required to ensure that cyclic control is maintained during OEI conditions. This excess power requirement may be overestimated, however, because VASCOMP is configured to calculate power required for vehicles with only conventional cyclic control. Through further research, the difference between conventional and CC cyclic control power requirements will be revealed.

This derivative engine approach, as opposed to the design an entirely new engine with the scaleable engine characteristics provided in the RFP, will decrease the Research, Development, Testing, and Evaluation (RDTE) and certification costs, as well as decrease the engine certification time period.

11.2 Additional Engine Characteristics

There are many other benefits to using a derivative of the PT6C-67A engine. This baseline engine was designed specifically for a tiltrotor application (BA-609). Therefore, its capability requirements are very similar to those of the Kingfisher. It was designed to operate in a tiltrotor attitude envelope. Thus, the pitch angle can range from 16º nose up to 110º nose-down. The engine also has reliable self-starting capability in the vertical and horizontal positions.[63] Additionally, the baseline engine has been validated for operations in known icing conditions.[64] Hence, the modifications to the PT6C-67A will predominantly be only for power requirements - not operational requirements. Figure 36 shows the cross-section of the PT6C-67A. The PT6C-KF will be very similar to this design – changes will be due to the application of IHPTET technology.

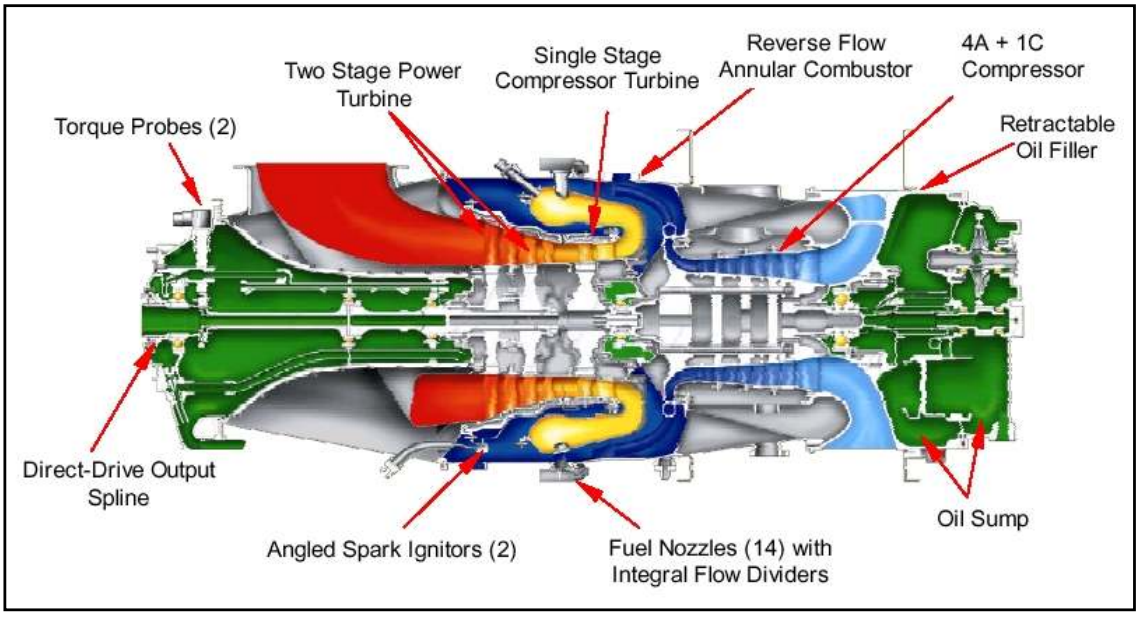


Figure 36: PT6C-67A Engine Cross-Section[65]

11.3 Technology Readiness

While the Kingfisher engine will be a derivative of an existing engine, it is assumed that the engine will be enhanced by IHPTET technology. The IHPTET Technology Program is a joint DoD/NASA/industry effort. The program objective is to develop and demonstrate advanced engine technologies that are capable of more than doubling the turbine engine power-to-weight ratio and reducing SFC by 40% relative to 1987 state-of-the-art engines. These goals are to be

achieved with no compromise in life and durability levels.[66] The assumptions in the RFP (25% reduction in SFC, 40% increase in power-to-weight ratio) translate these goals to present day terms.

The IHPTET program is scheduled to complete the second of three phases this year. IHPTET III (the third and final phase) will follow, and is scheduled to begin Engineering and Manufacturing Development (EMD) in Fiscal Year 2008 (FY08). IHPTET III technology is projected to be included in production engines by FY14.[67]

In the year 2000, the Joint Turbine Advanced Gas Generator (JTAGG) component of the IHPTET program demonstrated a 22% decrease in SFC and a 63% increase in power-to-weight ratio. These gains resulted from technological improvements in the compression systems, combustion systems, turbine systems, controls and accessories, and mechanical systems. The goals for IHPTET III are to achieve a 40% decrease in SFC and a 120% increase in power-to-weight ratio, thus substantially building upon the IHPTET I and II achievements. The key technologies that will enable these dramatic improvements include a forward swept splittered rotor, a forward swept split inducer impeller, a ceramic matrix composite (CMC) combustor liner, a cooled CMC turbine nozzle, cooled and uncooled monolithic ceramic turbine blades, magnetic bearings, and finger seals. [68]

With the achievements made thus far in IHPTET and with the aggressive pursuit of much higher goals, the IHPTET assumptions applied to the Kingfisher engine are very reasonable. The Kingfisher will initiate the certification process in 2007. By this time, the technology developed by IHPTET II+ will significantly enhance the PT6C-KF. The risk of assuming a 25% decrease in SFC and a 40% increase in power-to-weight ratio is considered low.

12 TILTROTOR CONVERSION

Conversion between helicopter and airplane flight modes is an important, but simple, process for the Kingfisher. Conversion is possible because the rotor-lifted speed range overlaps the wing-lifted speed range. Figure 37 depicts the Kingfisher's conversion corridor. This corridor was determined by calculating various trim positions in EVMCEP. The lower corridor limit is determined by wing stall and the upper limit is set by the maximum continuous power available. This allows the Kingfisher to fly through a wide range of airspeeds at different nacelle angles. As the gross weight of the aircraft increases, the tiltrotor conversion corridor decreases.

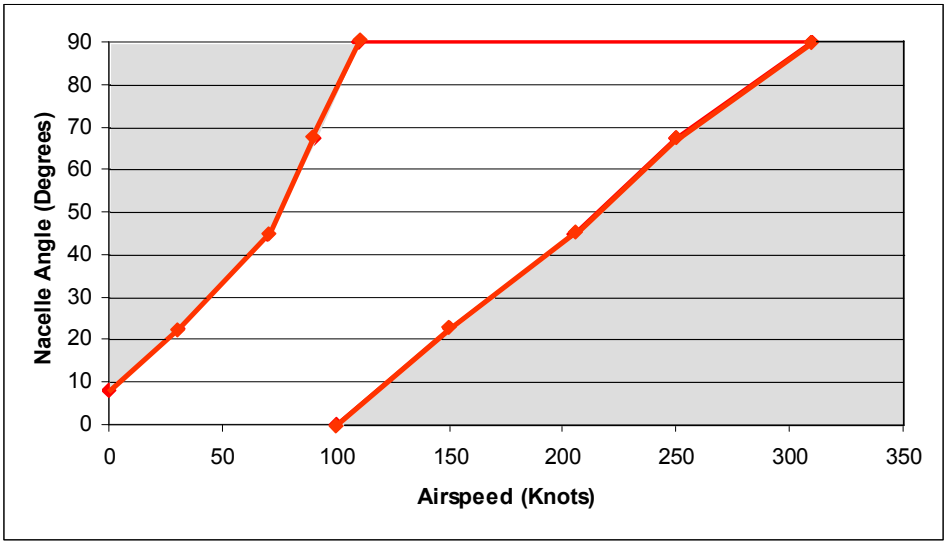


Figure 37: Tiltrotor Conversion Corridor

The Kingfisher control system is designed to minimize pilot workload during conversion. In helicopter mode, the Kingfisher depends on CC to provide rotor thrust variation for cyclic control. The pilot flies the aircraft with normal helicopter flight control inputs. These controls are gradually phased out during conversion as conventional airplane controls are phased in.[69]

The actual conversion mechanism will consist of two nacelle-mounted electric actuators, which mechanically pivot the nacelles to desired positions. The actuators will be mechanically linked to each other for redundancy (i.e., one actuator will be capable of moving both nacelles).

13 RELIABILITY/MAINTAINABILITY ANALYSIS

13.1 Reliability

The RFP called for an FCS reliability of less than one failure in 10^7 flight hours. The reliability analysis was completed using both deductive and inductive methods. For the deductive, or top-down method, a PRISM fault hazard analysis (FHA) and fault tree analysis (FTA) were used. An FHA is a qualitative analysis of component hazard modes and the resultant effects to subsystems. An FTA graphically identifies subsystems that are most critical to safe operation. As shown in Figure 38, the FCS has seven FCS subsystems: the rotor system, actuator system, fly by wire system, compressed air plumbing, computer system, mechanical controls, and "others."

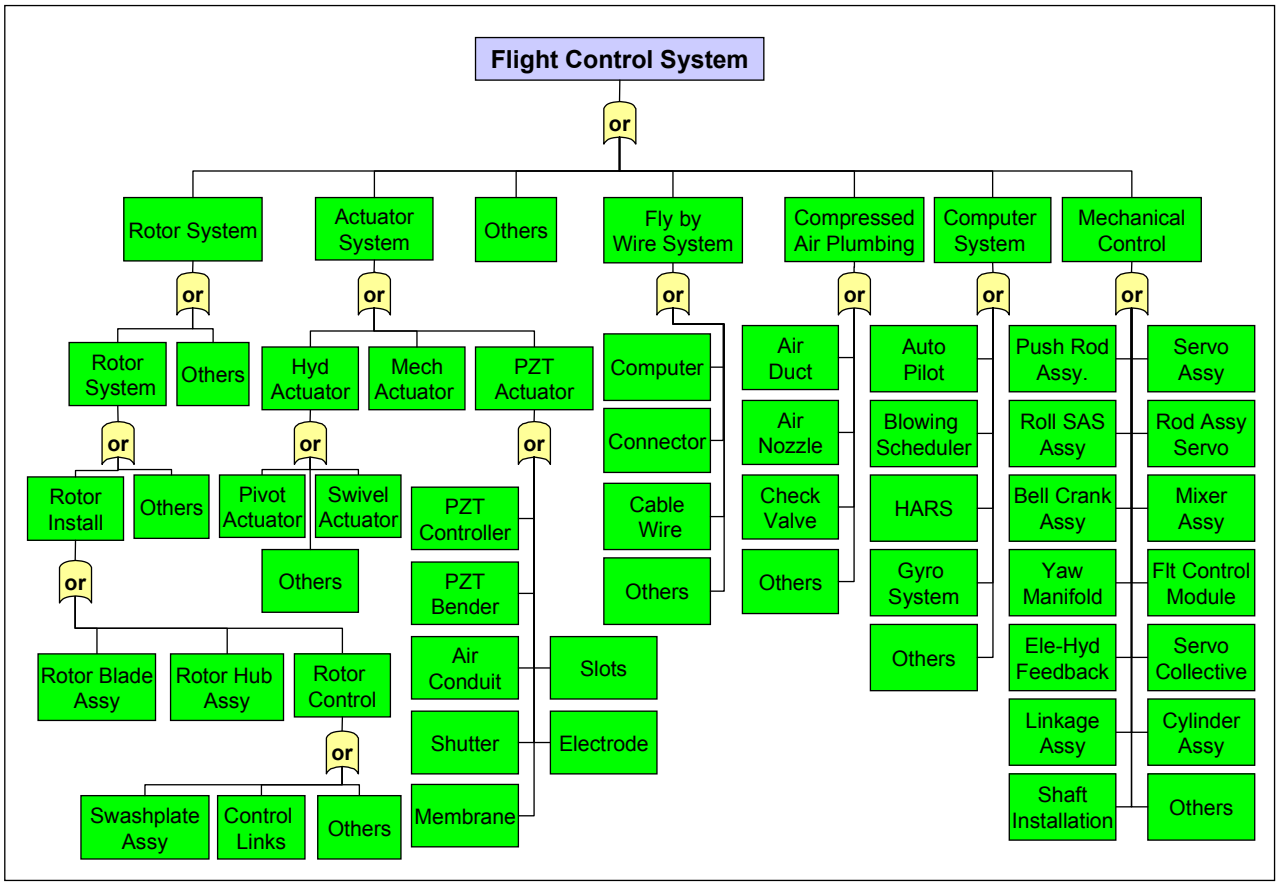


Figure 38: FCS Fault Tree

PRISM is a system-level failure rate assessment program based on a methodology developed by the Reliability Analysis Center (RAC) for the U.S. Air Force. PRISM software contains failure rates for RAC system models and RAC component data.

One of the benefits of using PRISM is that the software considers a process grade factor when calculating the system failure rate. This process grade factor is based on over 100 questions in subjects such as design, manufacturing, part quality, and system management. PRISM then takes this process grade factor and applies it to the system model equation to calculate the failure rate. We began the analysis with a CH-47D PRISM model that was previously analyzed at the Georgia Institute of Technology. This model was then modified based on the physical and functional arrangement of the Kingfisher FCS. With this model, the failure rate for the Kingfisher FCS was determined to be 0.97 failures in 10^7 flight hours. The failure rate breakdown of the various FCS components is shown in Figure 39. Of the seven FCS subsystems, the actuator system (28% of FCS failures) and the mechanical control system (26% of FCS failures) are the most likely to cause an FCS failure.

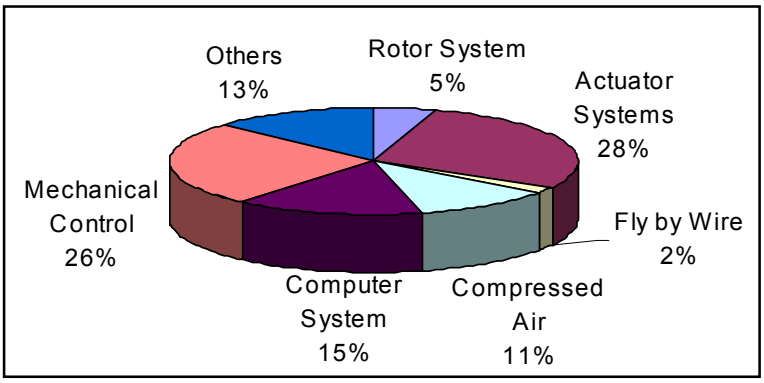


Figure 39: FCS Failure Rate Distribution

For the inductive, or bottom-up method, a failure modes and effect analysis (FMEA) was used. An FMEA was performed to identify results of probable component failure modes and to analyze their effects at a subsystem level.[70] The FMEA for piezoelectric actuators is shown in Table 14. This FMEA identifies the component, its failure mode, and its effect on the FCS, as well as additional details. A critical value, from the four FAA alternatives (Catastrophic, Critical, Marginal and Negligible), was assigned to each component failure mode.

Description	Function	Failure Mode	Phase	Detection Method	Failure Effect/ Corrective Action	Critical Value
Piezoelectric Bender	Provide Control Input	Fail to Control Input	Hover/ Conv.	PZT Actuator Health Indicator	Degraded Flt Control/ Info/System Status	Marginal
Air Conduit	Provide Compressed Air	Fail to Provide Compressed Air	Hover/ Conv.	Compressed Air Pressure Switch	Degraded Flt Control/ Land - Practicable	Critical
Shutter	Provide Blowing Control	Fail to Control Input	Hover/ Conv.	PZT Actuator Health Indicator	Degraded Flt Control/ Info/System Status	Marginal
Narrow Air Slot	Provide Compressed Air	Fail to Provide Compressed Air	Hover/ Conv.	PZT Actuator Health Indicator	Degraded Flt Control/ Info/System Status	Critical
Electrode	Provide Control Input	Fail to Control Input	Hover/ Conv.	PZT Actuator Health Indicator	Degraded Flt Control/ Info/System Status	Critical
Membrane	Provide Blowing Control	Fail to Provide Compressed Air	Hover/ Conv.	PZT Actuator Health Indicator	Degraded Flt Control/ Info/System Status	Marginal

Table 14: FMEA for Piezoelectric Actuator System

Another important phase of reliability analysis is risk management. Risk management allows the engineer to identify which subsystem or function requires preventive measures against adverse consequences. As shown in the hazard criticality matrix (Figure 40), all of the Kingfisher FCS subsystem failures were classified as moderate risk. For each subsystem, PRISM failure rates were used to categorize the probability. Although the mechanical control and actuator systems belong in the moderate risk category, a change in consequence from marginal to critical could shift the risk to high. Therefore, it is imperative to adhere to the current design standard and plan.

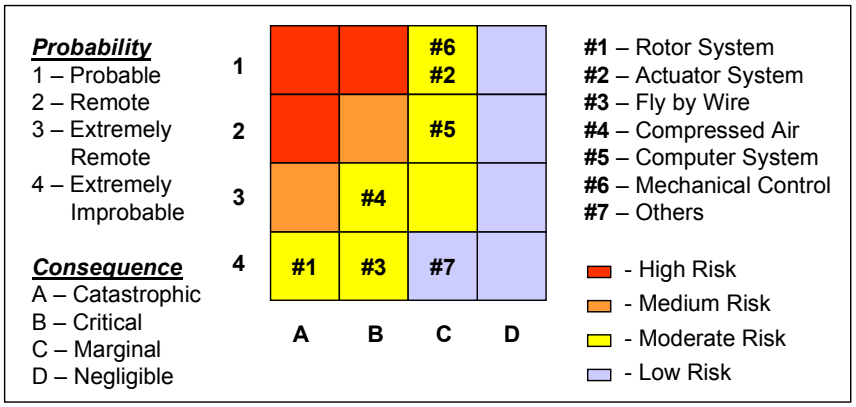


Figure 40: Hazard Criticality Matrix

Functional flow block diagrams were constructed to map the effects of possible hazards and to develop solutions for adverse effects. This process helped to verify previous reliability analyses as well as to identify required modifications to existing components to ensure safe operation. Figure 41 shows a scenario where piezoelectric actuators in the right rotor are damaged due to a blade strike. In this scenario, the main air conduit is cracked and so compressed air is no longer blown through the CC slots. The HMP detects this failure and shuts off flow to this blade. Although cyclic control authority is lost for the blade, authority for the rotor (and vehicle) is not lost. By adjusting the lift of the other blades (through CC blowing), and because the rotor system is stiff and gimbaled, the thrust vector can still be tilted to a desired value and so cyclic authority is retained.

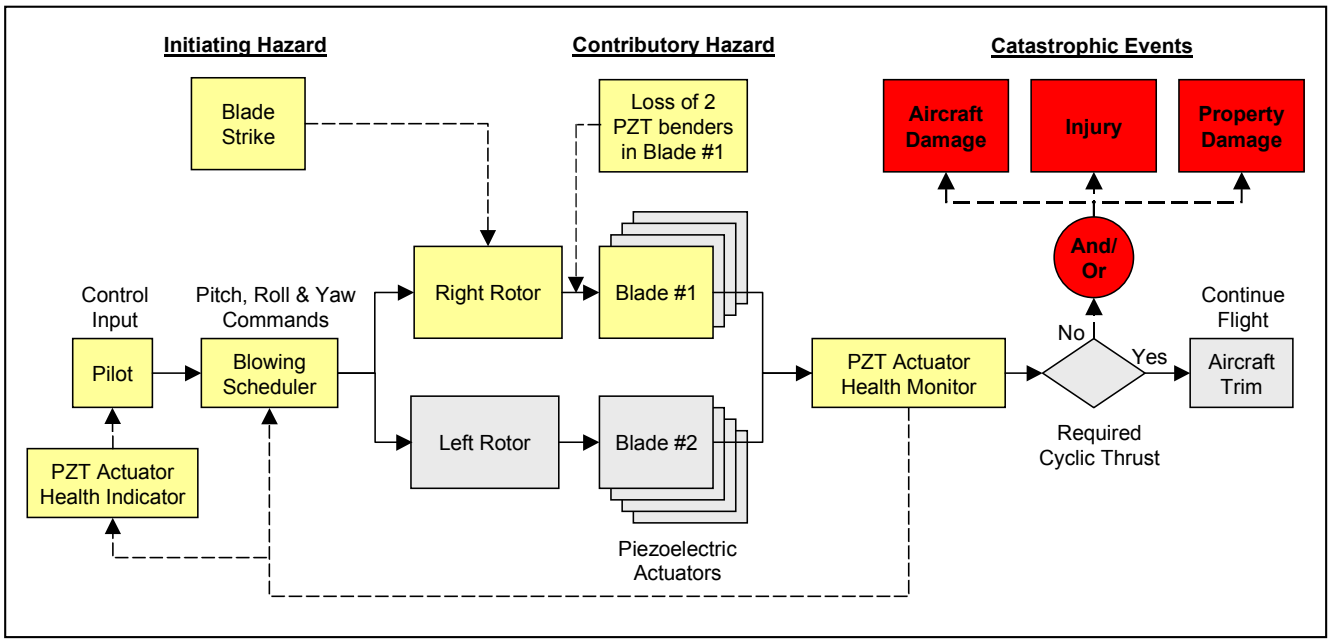


Figure 41: Functional Flow Block Diagram

13.2 Maintainability

The Kingfisher will use improved Flight Data Recording and Health and Usage Monitoring System (FDR/HUMS) technology for improved maintenance, enhanced safety, and reduced direct operating costs.[71] FDR/HUMS (shown in Figure 42) is currently used in modern commercial and military aircraft. Kingfisher maintenance personnel and crewmembers will have real-time indications of aircraft performance and degraded conditions. Current systems only provide for reactive measures when systems fail or exceed operating limits. However, the Kingfisher FDR/HUMS will provide maintenance personnel and crewmembers the overall condition of the aircraft and will alert them if there are known or forecasted failures.

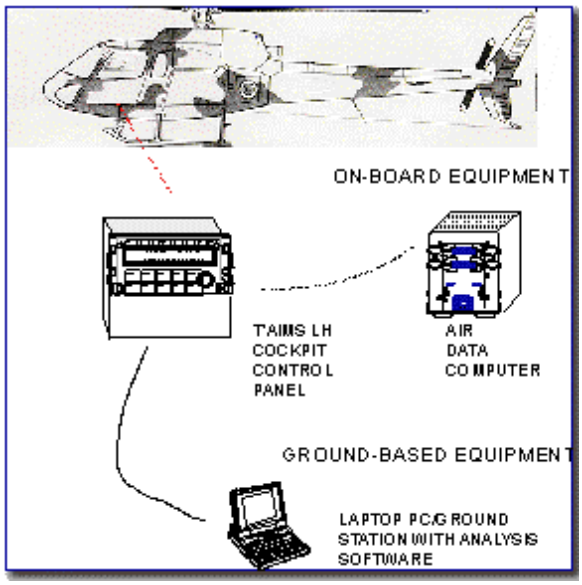


Figure 42: Health and Usage Monitoring System (HUMS)[72]

The Kingfisher's components are designed for easy maintenance through the use of common parts. The vehicle will use components configured as line replaceable units (LRUs) as much as possible. Particular emphasis will be placed on using LRU avionics components. This will decrease troubleshooting times and reduce the effort for related maintenance activities (e.g., more time is required to remove and replace multiple components in an effort to find the failed one; rather, related system components will be integrated into single LRUs). This will also decrease the number of required maintenance tools and support equipment. Aircraft compartments are designed for easy access and inspection panels are provided for hidden components. Aircraft logbook and supporting documentation will be automated so that data can be entered and retrieved with hand-held computers.

The Kingfisher will include a blade folding arrangement so that its total width (at the widest part of the vehicle) can be reduced from 65 feet to 39 feet. To accomplish this, the outermost blades (i.e., the two outside blades perpendicular

to the vehicle's longitudinal axis) will be pivoted about one blade pin and then fixed with a bracket to their adjacent blades. This arrangement will present technical challenges, however, since the blades have pneumatic conduits connecting the hub to each blade. These conduits must maintain their integrity despite blade removals and reattachments.

The Kingfisher FCS will be more reliable than that of a typical helicopter. Generally, the tiltrotor structural load spectrum in cruise mode (axial mode) is better than that of helicopters in cruise mode (edgewise inflow with high oscillatory blade loads). Because of this decrease in oscillatory loads, the Kingfisher's time-change components will likely have longer times-between-overhauls (TBOs).[73]

14 COST ANALYSIS

Two simulation programs were used to assess the development and manufacturing costs of the Kingfisher. First, the cost module in VASCOMP was used to determine these costs and second, a PC-based tiltrotor/helicopter model, obtained from Bell Helicopter, was used.[74] The cost model in VASCOMP produced values which were extremely low (compared to the Bell model and compared to expert opinion). Because of the suspicious nature of the VASCOMP cost data, the Bell model was used as the sole source for analysis. This model was developed based on V-22 Osprey development and production data in addition to estimated data from the BA-609. The model was verified by Bell Helicopter against available baseline data so its accuracy is likely to be high.

A variety of design parameters were entered into the model, including actual component weight data obtained from VASCOMP. This improved the accuracy of the model when compared to the model's own macro-level sizing and weight routine based on vehicle gross weight.[75] Some of the various assumptions/RFP requirements entered into the model are listed in Table 15.

Cost Model Baseline Assumptions and Inputs	Source
300 Aircraft Production Run	RFP
48 Aircraft per Month Production Rate	RFP
Approximately $75 per Hour Labor for Engineering/Management	Georgia Tech Staff
Approximately $50 per Hour Labor for Assembler	Georgia Tech Staff
1 Flight Test Prototype (Model Develops Prototype Cost)	Georgia Tech Staff
1 Each: Ground Test Vehicle; Static Test Article; and Fatigue Test Article (Each at 80% First Unit Cost)	Georgia Tech Staff
Used VASCOMP Component Weight Data	VASCOMP
Used Model Learning Curve Values	PC Based Cost Model
25% Increase in FCS Design Cost and Flight Test Cost	Assumption

Table 15: Cost Model Assumptions and Input

This model calculated both non-recurring development costs and recurring manufacturing costs (recurring costs did have some relatively minor non-recurring production tooling costs added). The baseline vehicle was considered to be an advanced flight control system tiltrotor with primarily composite structures. The FCS development costs were increased by 25% (compared to a traditional FCS) in order to compensate for the increased work required to design, test, and certify such a system. The flight test costs were also increased by 25% to adjust for increased vehicle testing. The total development costs (by discipline/category) are depicted in Table 16 (all dollars are in year 2000).

Total Development Cost	
Engineering	**$258,282,000**
Design	$174,718,000
Flight Test	$13,129,000
Component Test	$53,059,000
Systems Engineering/Project Managemer	$17,376,000
Manufacturing Engineering	**$44,538,000**
Planning, Loft, Other	$42,100,000
Project Management	$2,438,000
Tooling	**$63,432,000**
Tool Make	$45,822,000
Outside Tooling	$17,610,000
Manufacturing	**$81,559,000**
Prototype (1)	$15,338,000
GTV (1) STA (1) FTA (1)	$36,810,000
Flight Test	$5,414,000
Component Test	$23,997,000
Logistics	**$1,213,000**
Other	**$15,837,000**
Travel and Per Diem	$3,417,000
Direct Expense	$12,420,000
Total Program	**$464,861,000**

Table 16: Total Development Cost

The next task was to model the non-recurring production costs. All of the previously mentioned assumptions were again used to determine these costs. Table 17 depicts a by-system breakdown of these costs. The table also includes the amortized (over 300 aircraft) development costs in order to determine the average total cost per airframe.

Total Average Cost by System (300 Acft Production)				
Section	**Labor**	**Material**	**Subcontract**	**Total**
Wing	$79,907	$23,950	$117,452	$221,309
Rotor	303,282	112,464	190,556	606,303
Tail	60,024	94,775	92,116	246,915
Fuselage	609,167	212,645	12,674	834,486
Landing Gear	15,978	4,221	247,991	268,190
Nacelles	152,520	152,989	20,159	325,668
Powerplant	16,065	100,471	1,338,395	1,454,932
Drive System	163,085	112,984	380,517	656,587
Flight Controls	68,268	107,429	800,851	976,548
Auxiliary Power Unit	1,726	64	250,550	252,340
Instruments	18,521	946	618,859	638,326
Hydraulics	22,840	6,402	238,256	267,497
Electrical	25,724	15,659	44,156	85,539
Avionics	26,734	2,796	369,924	399,454
Furnishings and Equipment	18,209	13,387	19,673	51,269
Air Conditioning	8,155	20,546	21,717	50,417
Anti-icing	74	0	34,826	34,900
Load and Handling	62	1,352	0	1,414
Final Assembly	210,871	0	0	210,871
Subtotals	1,801,211	983,080	4,798,672	7,582,963
Non-Recurring and Other Production Costs - Amortized over 300 Aircraft				270,329
Total Average Production Cost				7,853,291
Development Costs - Amortized over 300 Aircraft				1,549,537
Total Average Per Unit Cost				**$9,402,828**

Table 17: Total Average Cost per Aircraft (By System)

In order to determine the effects of various aspects of the design (such as material selection), development and production costs were calculated for several design scenarios (please see Table 18). Two of the scenarios considered the Kingfisher being developed as a variant of the BA-609. This scenario is quite realistic since the Kingfisher is very similar in size and performance to the BA-609. For the BA-609 variant scenario, aircraft systems were assigned values representing the level of development required for the system. The rotor and flight control systems, for example, were considered to be completely undeveloped. In contrast, the landing gear was assigned a value of 75% designed. Other systems were assigned varying levels of development as appropriate.

Case	Development Type	Flight Control System	Materials	Total Development Cost	Cost per Airframe
1	New Acft	Advanced	Composite	$464.86 mil.	$9.40 mil.
2	New Acft	Advanced	Metal	$460.57 mil.	$9.15 mil.
3	New Acft	Traditional	Composite	$449.42 mil.	$9.35 mil.
4	BA-609 Variant	Advanced	Composite	$304.44 mil.	$8.87 mil.
5	BA-609 Variant	Traditional	Metal	$286.24 mil.	$8.57 mil.

Table 18: Development and per Unit Aircraft Costs

Case #1 represents the anticipated production version of the Kingfisher (i.e., advanced FCS vehicle constructed with composite materials). The selection of composite materials was made primarily because of their improved strength-to-weight ratio and because the Kingfisher's operating environment (near saltwater) would cause corrosion problems with metal structures. By comparing Case #1 with Case #2, one can determine the costs associated with the decision to use composite materials. The cost increase per airframe is about $250,000. This cost increase reflects only acquisition cost and does not reflect savings in operating cost due to decreased weight and increased corrosion resistance. These savings are expected to be large and will more than compensate for the slightly increased acquisition cost.

Similarly, by comparing Case #1 with Case #3, one can determine the acquisition cost increase associated with the advanced FCS. The acquisition cost increase per airframe is $50,000 in this case. Again, this analysis only considers macro-level increases in FCS development cost and in flight testing (as described above). The advanced FCS will be mechanically simpler, have fewer components, and will require less scheduled maintenance. These factors will combine to somewhat reduce both acquisition and operating costs.

Case #4 represents the Kingfisher development as a variant of the BA-609 (please note that the vehicles in Cases #1 and #4 are identical; only the development process is different). With a decrease in development cost, the per unit cost also decreases -- by $530,000 per unit. This represents very sizeable savings, which adds viability to this development scenario.

Case #5, also a variant of the BA-609, depicts the cheapest (only in terms of acquisition cost) method of producing a tiltrotor vehicle capable of performing the mission of the RFP. These acquisition savings, however, will be lost due to the increased operating costs as described above.

15 AFFORDABILITY

As with any aviation system, the Kingfisher must be affordable to operate in order to be a viable product. Compared to current U.S. Coast Guard aircraft (both fixed and rotary wing), the Kingfisher offers dramatic improvements in terms of operating costs (fuel, labor, and maintenance costs). With nearly twice the cruise speed of currently used rotorcraft (the HH-60 and the HH-65), the Kingfisher can reach a rescue area more quickly and can search a larger area in a given amount of time.

The Kingfisher is expected to have an actual operating cost of $900 per flight hour (however, because of the cost calculation methods used by the Coast Guard, this cost figure has been increased by 50% in order to maintain consistency for cost comparisons).[76] This value was calculated using performance data (such as fuel burn rate), cost data from the

aircraft's VASCOMP calculation, and by comparison to existing aircraft (in particular, the BA-609). This value is most likely conservative in nature, as it does not include maintenance cost savings resulting from the simplified flight control system.

The Coast Guard uses three aircraft for short and medium range SAR missions which are defined as missions up to 100 nm and 300 nm, respectively. These aircraft are the HH-65 Dolphin (9,200 lb. twin-engine helicopter); the HH-60 Jayhawk (21,884 lb. twin-engine helicopter); and the HU-25 Falcon (32,000 lb. twin-engine jet airplane).[77] Table 19 depicts some basic cost and performance data for these aircraft (and the Kingfisher). The data presented is general in nature and is intended primarily for comparison purposes.

Aircraft	Cruise Speed (Knots)	Max Range (NM)	Time to Max Range (Hours)	Cost per Flight Hour (Dollars)	Rescue Capability
HH-65	120	300	2.50	$1,400	Yes
HH-60	140	700	5.00	$1,700	Yes
Kingfisher	260	900	3.46	$1,350	Yes
HU-25	350	1940	5.54	$2,000	No

Table 19: SAR Aircraft Characteristics

Table 20 depicts search performance and cost data for the aircraft considered. The search sweep width value represents the search corridor width of an aircraft in forward flight. These values are considered different for fixed and rotary wing aircraft, as depicted.[78] The maximum search area is simply the maximum range multiplied by the search sweep width. The next column represents the time required to search 1000 nm^2 and is the maximum search area divided by the flight time to maximum range. The cost per 1,000 nm^2 searched is the time for the search multiplied by the cost per flight hour. The final column depicts each aircraft's search cost increase relative to the Kingfisher.

Although the HU-25 has only a 41% cost increase over the Kingfisher, this value represents just the search phase of the SAR mission. The cost of the actual rescue could add significantly to the total mission cost since a rotary wing would be required during this phase of the mission.

Aircraft	Search Sweep Width (NM)	Max Search Area (NM^2)	Time per 1000 NM^2 Searched (Hours)	Cost per 1000 NM^2 Searched (Dollars)	Cost Increase vs. Kingfisher (%)
HH-65	9.2	2,760	0.906	$1,268	125%
HH-60	9.2	6,440	0.776	$1,319	134%
Kingfisher	9.2	8,280	0.418	$564	----
HU-25	7.2	13,968	0.397	$794	41%

Table 20: SAR Aircraft Mission Cost Comparison

Clearly, the Kingfisher provides significant cost savings when compared to currently used Coast Guard aircraft. Additionally, since the Kingfisher can search a greater area per sortie than the other rotary wing aircraft, it would require fewer total sorties during an extensive search. This improves the Kingfisher's mission cost performance beyond the values depicted above.

Concerning long-term costs, the Kingfisher's dramatically improved mission performance would result in a smaller fleet requirement for a given mission capability. Its ability to search roughly twice as much area in a given period of time reduces flight hour requirements by 50% and allows it to conduct more searches at lower costs.

16 MANUFACTURING

Manufacturing processes and tooling are the elements that control the success and cost of composite components.[79] These processes include elements of material selection, tool selection, thermal expansion effects, processing, cost, safety, and health. Approaches used in the manufacturing of this aircraft must recognize the risks for non-traditional hardware (i.e. composite structures) design.

Manufacturing methods for this aircraft include filament winding, cocuring, and thermoforming (please see Section 9.8, Materials). This aircraft has been designed with simplicity as a primary goal. For instance, curve complexity has been kept to a minimum to avoid complicated machining problems. In addition, symmetric design has been incorporated whenever possible to decrease the number of stocked parts and to simplify the aircraft assembly.

Composite material selection is an important aspect of manufacturing this aircraft. Cost, ease of fabrication, potential commercial availability, multiple material sources, material specifications, and the potential to be used in an automated manufacturing plant must be considered. For example, the fabrication methods of both thermoplastic and thermoset composites seem similar at the onset. However, major processing differences exist such as chemical reactions, cycle time, temperature range, pressure required, and viscosity. These factors have a huge impact on the tools selected to complete the fabrication process.

Fabrication processes should be identified by the manufacturing facility during the conceptual design phase. Fabrication complexity could potentially increase the cost of production. Thermal expansion effects of the material must be considered when a composite is cocured. This is especially important in the construction of the Kingfisher's airframe.

Safety and health considerations are the final elements in the manufacturing process of this aircraft. Since most of the chemicals used to manufacture the composites are considered highly toxic, the manufacturing process becomes more

complex and hazardous. Industrial health requirements (such as personal protective equipment and waste disposal) will add a measure of cost to the manufacturing process.

The first Kingfisher is to be produced in January of 2015. Four aircraft will be produced per month, with total production anticipated to be 300 aircraft. Thus, the production run will last around 6.25 years. The aircraft is projected for certification at the end of 2013 (please see Section 18.1, Certification Timeline). This timeline allows a full year for optimizing the manufacturing methods and facilities, and for improving upon the manufacturing practices developed during prototype production.

17 NOISE CONSIDERATIONS

Noise is one of the most critical environmental concerns involving the design of this aircraft. In order to operate around both commercial and residential areas, the operating noise of the vehicle needs to be minimized. There are two primary ways to reduce the noise produced by a tiltrotor aircraft. One is by designing an inherently quiet rotor system. This requires significant lead-time and involves complex aeroacoustic and structural design tradeoffs. The Kingfisher's advancing tip Mach number during cruise is 0.75 (in helicopter mode at 100 knots), which will limit its external noise production. The second approach is to make use of the nacelle tilting capability of the tiltrotor, which allows the aircraft to fly a specified flight path at a number of different rotor operating conditions.[80] Through design, analysis, and testing, the Kingfisher takeoff and approach procedures will be developed to minimize noise.

Noise factors have the greatest impact on the surrounding areas during the approach and take-off stages of flight. Typically, this aircraft will depart and arrive mainly from coastal verti-ports in support of Coast Guard operations. This aircraft is unique because it possesses a wide range of speed and vertical rates of climb or descent that work together to limit noise emission levels. This is achieved mainly by varying the nacelle angles during climb and descent.

Most of the sound energy from this aircraft falls into the low-frequency noise category. This type of noise has a long range and is usually very difficult to shield. A low-frequency noise signature can create vibrations in buildings and other structures. Testing will reveal the level of low frequency produced by the Kingfisher, and operating procedures will be developed to mitigate the impact on structures. The Kingfisher mission will also aid in avoiding structures, as most of its mission time will be over water.

Another major noise consideration is the noise decibel levels within the fuselage. The noise level of a proprotor operating close to the fuselage will be extremely high. Approximately 1% of the Kingfisher's gross weight is dedicated to both active and passive noise cancellation systems. Most passive techniques are used to cancel out high-frequency noise

emissions. A few of these techniques include vibration mounts, insulation, silencers, and damping treatments. However, these treatments can be large, bulky, and heavy when used to treat low-frequency noise. Active noise reduction methods are used to treat the low-frequency noise emanating from the engines and proprotors. Active noise cancellation units are much smaller and lighter than passive devices. Speakers in the wall panels can reduce noise generated by the proprotor tips passing the aircraft fuselage.[81]

18 CERTIFICATION

The certification of a new aircraft with advanced rotor controls is a complex task, requiring a great amount of planning, coordination, and partnership with the Federal Aviation Administration (FAA). The certification process also requires strict adherence to guidelines and regulations as well as prudent execution of the certification plan in order to minimize certification costs and time as well as to optimize the safety and operability of the aircraft. To illustrate the complexity of this task, Figure 43 lists the regulatory documents that must be adhered to for certification.

Federal Aviation Administration	FAR PART 11	General Rulemaking Procedures
	FAR PART 21	Certification Procedures for Products and Parts
	FAR PART 25	Airworthiness Standards: Transport Category Airplanes
	FAR PART 29	Airworthiness Standards: Transport Category Rotorcraft
	FAR PART XX	Airworthiness Standards: Transport Category Powered Lift Aircraft
	FAR PART 33	Airworthiness Standards: Aircraft Engines
	FAR PART 34	Airworthiness Standards: Fuel Venting and Exhaust Emission Requirements for Turbine Engines Powered Airplanes
	FAR PART 36	Noise Standards: Aircraft Type and Airworthiness Certification
	FAR PART 183	Representatives of the Administrator
	AC 20-107A	Composite Aircraft Structure
	AC 25.1309-1A	System Design and Analysis
	AC 29-2A	Certification of Transport Category Rotorcraft
	FAA Order SW8100.4A	Rotorcraft Directorate, Aircraft Certification Service, Standard Practices
	FAA Order 8100.5	Aircraft Certification Directorate Procedures
	FAA Order 8110.4A	Type Certification Process
	FAA Order 8110.37A	Designated Engineering Representative (DER) Guidance Handbook
Other	RTCA/DO-160C	Environmental Conditions and Test Procedures for Airborne Equipment
	RTCA/DO-178B	Software Considerations in Airborne Systems and Equipment Certification
	SAE ARP 926A	Fault/Failure Analysis
	SAE ARP 4754	Certification Considerations for Highly Integrated or Complex Aircraft Systems
	SAE ARP 4761	Guidelines & Tools for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

Figure 43: Certification Documents[82]

To thoroughly address the Kingfisher Certification Plan is beyond the scope of this proposal. What follows is a general description of the certification timeline and a discussion of the FCS, Noise and Crashworthiness & Safety Certification Considerations.

18.1 Certification Timeline

The FAA normally grants a five-year certification period to a manufacturer in order to certify an aircraft with a new design. The Kingfisher, however, is unique because it will be among the first tiltrotors to undergo the certification process. More importantly, the innovative advanced rotor control system will require stringent certification procedures governed by regulations that have yet to be written. Therefore, we will request a seven-year certification period. The design process (preliminary/configuration/detailed design) will be completed by the end of 2006. In early 2006, we will request a Preliminary Type Board Meeting with the FAA to establish a certification period from the beginning of 2007 to the end of 2013. This will allow one year (2014) to optimize the manufacturing program before initiating production of the Kingfisher at the beginning of 2015. Figure 44 highlights the primary tasks during the certification period as well as approximate time allocations in order to complete those tasks. Many tasks are not shown, such as the coordination meetings between the Design Engineering Representatives and the FAA Certification Office, which would be detailed in a comprehensive certification plan.

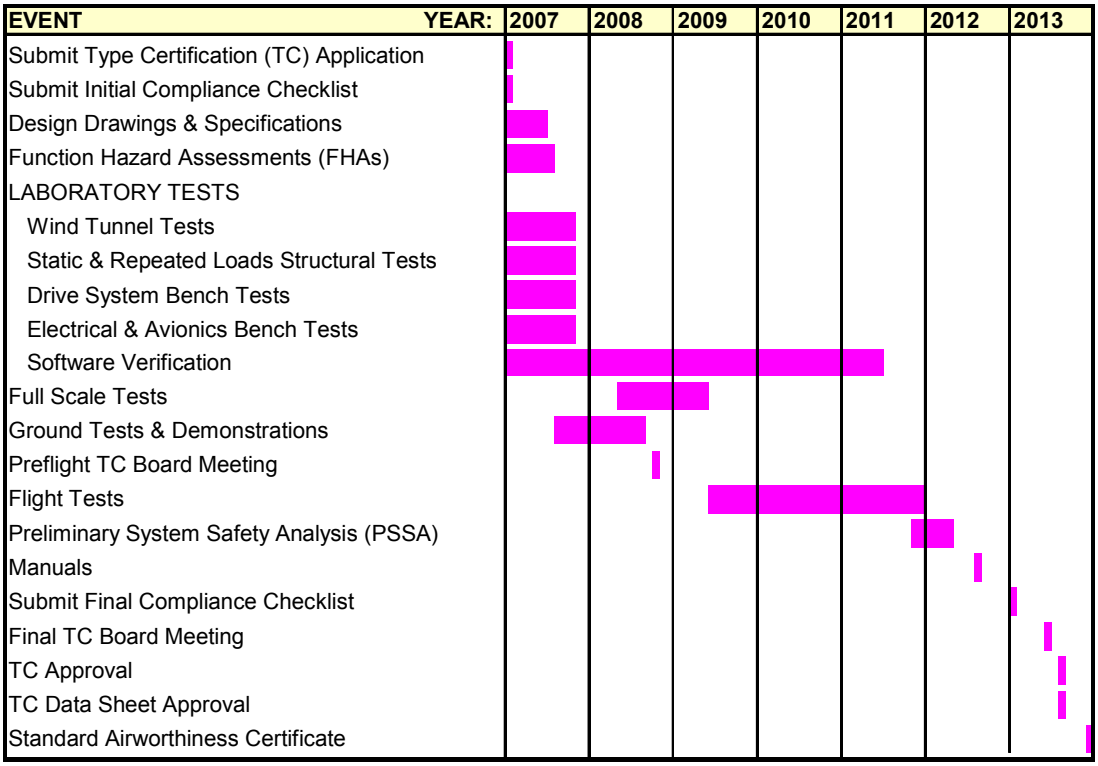


Figure 44: Certification Timeline

18.2 FCS Certification Considerations

The FCS consists of both hardware and software components that include aerodynamic control surfaces, the pylon/nacelle conversion system, hydraulics, cockpit controls, and digital fly-by-wire electronics. It will be the

manufacturers' responsibilities to qualify (to the specifications developed by the design team) all hardware components. The FCS will be certified through means of design, analysis, testing and evaluation.

Failure analysis is of great importance for FCS certification. As previously discussed in Section 13.1, Reliability, an FHA and an FMEA must be conducted to show that the probability of failure is less than 1 in 10^7 flight hours. The preliminary analysis indicates that the reliability meets this standard. However, the FCS software and hardware (when physically possible) must be set up and tested within the laboratory to verify the reliability estimate. Thus, the reliability analysis must be an iterative process, from simulation to model testing to ground tests to flight tests.

The FCS laboratory model will not only be useful for the reliability analysis, but will also serve to develop and verify the flight control computers and related systems functionality (including hydraulics, electrical, and avionics). Load testing will be conducted. This testing will provide a means to evaluate the pilot warning system. All flight control software may be developed and validated within the laboratory prior to any flight testing.

After extensive lab testing, the final testing of the FCS will occur in flight. The AFCS, to include all autopilot functions, must demonstrate compliance during final phases of flight testing.

18.3 Noise Certification Considerations

The Kingfisher must be certified in accordance with Federal Aviation Regulation (FAR) Part 36, "Noise Standards." Because of its tiltrotor design, the Kingfisher must adhere to both the "helicopter" and "propeller-driven airplane" noise regulations contained within Part 36. For the helicopter mode, Part 36 contains very specific measuring procedures and noise limits for a standard helicopter takeoff, fly-over, and approach profile. These procedures and limits must be modified to accommodate the unique profile of the Kingfisher tiltrotor, which will execute all three flight modes during normal takeoff, fly-over, and approach operations. It is anticipated that the noise limit for the fly-over mode will be the same as that currently published for the propeller-driven airplane. This limit is 88 dB.[83]

It is anticipated that by 2007 (the proposed start date of the Kingfisher certification period), Part 36 will be amended to accommodate civil tiltrotor certification. The BA-609 is scheduled to complete noise certification well before 2007. Specific noise certification procedures will be developed for the BA-609. It is reasonable to assume that the FAA will publish a generalized version of these certification procedures for tiltrotor aircraft. These regulations will include specific measuring procedures and noise limits for a tiltrotor takeoff, fly-over, and approach profile. The existing noise standards will be tailored to accommodate the tiltrotor as it transitions between helicopter, conversion and airplane flight modes.

To ensure that the Kingfisher meets the noise requirements, the tip Mach number was reduced as much as possible (0.75 at 100 knots, helicopter mode). Although this low Mach number will reduce aircraft noise, the flight profile for noise certification must be simulated in laboratory tests (before prototype vehicles are built) to ensure compliance. During the actual flight tests, the FAR measuring and recording procedures will be strictly followed. To ensure accuracy and reduce the number of required test runs, the testing procedure will be closely monitored. This monitoring process will also help to minimize certification costs.

18.4 Crashworthiness & Safety Certification Considerations

Many of the design aspects addressed in this section have been addressed in previous sections, such as those aspects pertaining to cockpit and cabin design. Additionally, crashworthiness was addressed in detail in Section 9.7, Emergency Situations and Crashworthiness. The purpose of this section is to succinctly address specific design aspects as they relate to certification, while minimizing repetition. While FAR Part XX was the source document for the following discussions, again the expectation is that the FAA will publish an amendment for tiltrotor certification prior to the Kingfisher certification period.

Landing Gear: The landing gear will be certified through analysis as well as ground and flight tests to demonstrate compliance with the requirements pertaining to shock absorption, wheels, tires, and brakes. Appropriate drop tests shall be conducted.

Cockpit: The cockpit is designed to optimize duty performance and controllability, while minimizing vibration, noise, and windscreen glare. The cockpit will be weatherproof, preventing any rain or snow leakage in flight. Pilot and copilot view will be optimized; any shortcomings will be mitigated by state of the art cockpit displays. The cockpit doors are designed to meet requirements for emergency exit certification. These design efforts will facilitate cockpit accommodation certification.

Cabin: The cabin design meets the certification requirements for emergency exits, arrangement, markings, lighting, access, seats, restraints, and attachments. Compliance with these requirements will be accomplished through demonstration. Hoist operations as well as limited cyclic control by cabin crew members will also be demonstrated to the FAA.

Emergency Evacuation: The Kingfisher must be designed to provide a means for rapid evacuation of all personnel in the event of a crash landing. Compliance with this requirement will be shown by design, analysis and inspection.

Fire Protection: Fire extinguishers will be located and easily accessible in both the cockpit and cabin areas. All crew and passenger compartments will be constructed from flame resistant materials. "No Smoking" placards will be visible to all personnel. All ventilating air ducts will be fireproof.

Engine Fire Detection/Protection System: Fire detection systems will be developed to immediately sense engine and APU fires and provide adequate warning to the pilot and copilot. For the fire protection system, each nacelle (and the APU compartment) will contain a fire extinguishing bottle which will release extinguishing agents in the case of fire. Fire doors will close the engine cooling air inlets. Additionally, the nacelle design provides for the required firewalls and designated fire zones.

Ice Protection/Icing Certification: It is assumed that the Kingfisher will have to operate in moderate icing, which may occur under the following conditions: ambient air temperature is 4ºC or below, visible liquid moisture is present, and the liquid water content (LWC) of the outside air is from 0.5 to 1.0 grams per cubic meter.[84] Through analysis, simulation, and ultimately flight testing, the Kingfisher will demonstrate compliance with the de-icing requirements.

Floatation/Ditching Certification: A floatation kit will be designed to allow safe egress of personnel in the case of an emergency water landing. The primary floatation devices will be large inflatable bladders located under the fuselage, which will be activated in the event of a water landing. The floatation kit will also include nacelle and wing tip floats. Additionally, the fuselage will lend natural buoyancy due to its design and materials. Compliance with the floatation and ditching requirements will be shown through analysis and simulation.

19 ADDITIONAL APPLICATIONS

The Kingfisher has a cruise speed of 260 knots and a range of 700 nm. The cabin has 323 square feet available (after removal of cabinets). The cabin is designed to carry two crewmembers, 2 evacuees, rescue and survival equipment, and Medical/EMS Equipment weighing a total of 1,920 pounds. The cabin can feasibly be configured to carry up to ten passengers (with one cabin crewmember). The Kingfisher has a hoist capability of 600 pounds. It can take-off and land vertically, so it can go virtually anywhere. The Kingfisher can fly at altitudes of 15,000 feet in IMC weather at night in moderate icing conditions. Its cost is $9.4 million. These are the key parameters when considering how the Kingfisher may be used for operations beyond those specified in the RFP.

Given the cost, the potential Kingfisher customers are government agencies and medium to large private companies/corporations. Typically, aircraft for personal use are purchased to provide transportation from point to point. The Kingfisher will likely not compete with far cheaper airplanes and helicopters for such use.

Government agencies and private organizations may use the Kingfisher, however, for a wide range of purposes. In off-shore oil drilling operations, the Kingfisher could fulfill basic personnel and supply transportation, emergency medical transportation, emergency supply operations, and its primary mission of search and rescue operations. Logging companies could use the Kingfisher's combination of range, speed, cabin capacity, and hoist capability to improve efficiency. Border patrol agencies could use the Kingfisher for the same reasons, and also take advantage of its search capabilities to find illegal aliens along borders. Park and wildlife agencies could use the Kingfisher for wilderness rescue operations (from mountains, lakes, canyons, etc). The Kingfisher would make an excellent high-speed MEDEVAC aircraft, able to go anywhere the current fleet of MEDEVAC helicopters can go and at a much faster rate. The Kingfisher could be used in humanitarian efforts, transporting thousands of pounds of medical equipment and supplies, per sortie, to remotely located people, perhaps suffering the ravages of a devastating flood. With its capability to be configured into a passenger craft, the Kingfisher could quickly transport up to 10 members of any organization from one meeting to another in a very short time. Corporate executive committees could travel from verti-port to verti-port at 260 knots as opposed to plodding along at 150 knots in a helicopter.

For organizations that can afford the Kingfisher, its combination of speed, vertical landing ability, cabin flexibility, passenger capacity, and hoist capabilities make it a very attractive alternative to many applications that are currently fulfilled by helicopters and small airplanes. The preceding discussion, of course, is not limited to U.S. customers. By selling the Kingfisher worldwide, the aircraft cost will decrease and the market will correspondingly expand.

20 CONCLUSIONS

The Kingfisher search and rescue aircraft represents a measured technological step forward in terms of flight control design and smart material integration. While the collective system remains mechanical, the cyclic system integrates eight piezoelectric bimorph benders into each of the blades. These benders modulate a compressed air flow which, leaving through jet slots in the trailing edge of each blade, varies the cyclic thrust of the rotor disk due to the Coanda effect.

The flight control system will feature neural network adaptive control technology and will use hub-located processors to manage the flow in each blade as well as to monitor system health. These processors also minimize fixed to rotating signal requirements and will allow future performance upgrades through software-only changes.

Each of the two rotors will be stiff-in-plane and gimbaled. Already used on existing tiltrotors, this type of rotor is a proven configuration and will also reduce the impact of single-blade circulation control failures.

Fly-by-wire technology provides the interface between cockpit signals and FCS actuator signals. These types of systems are also already is use and allow for tremendous flexibility in terms of control system tailoring.

The Kingfisher cockpit and cabin crew stations feature the latest advances in avionics, navigation, and night vision technologies. Designed with emphasis on customer desires, the all-glass cockpit provides for outstanding integration between environment, vehicle, and crew.

Constructed primarily from composite materials, the Kingfisher will be strong, light, and very resistant to corrosion. The Kingfisher features many of the latest advances in terms of crashworthiness and survivability. These systems include vehicle floatation devices and cockpit airbags, among others.

With its dramatically improved performance, the Kingfisher will be significantly more affordable to operate compared to currently used U.S. Coast Guard aircraft. Mission cost savings of 50% will likely be realized (not including savings resulting from fleet size reductions).

As with any new design that incorporates innovations such as the CC concept, certification of the Kingfisher will be challenging. However, the planned seven-year certification period will allow for the development and execution of new certification procedures. The design process will continue for the next five years, prior to the 2007 certification initiation date. Since BA-609 certification will precede that of the Kingfisher, FAA tiltrotor certification procedures will be established and tested. This is expected to greatly simplify the certification process for the Kingfisher.

Simple in concept yet practical in application, the Kingfisher's flight control system is an evolutionary progression from traditional to advanced controls. Because of this relative simplicity, the Kingfisher has great potential to be designed, certified, produced, and delivered by 2015. With better performance and system integration than any other rotary wing aircraft, the Kingfisher is the best vehicle for tomorrow's search and rescue missions.

[1] Johnson, W., Helicopter Theory, Dover Publications, Inc., Mineola, New York, 1980, pp. 12.
[2] "2001 Request for Proposal (RFP) for Advanced Rotor Control Concepts", Sponsored by The Boeing Company and The American Helicopter Society International.
[3] Junger, S., The Perfect Storm: A True Story of Men Against the Sea, W.W. Norton and Company, May 1997.
[4] Schrage, D.P., "Vehicle Synthesis for Advanced VTOL Aircraft", Georgia Institute of Technology, Department of Aerospace Engineering, Rotorcraft Design I, Class Notes, Atlanta, Georgia, Fall 2000.
[5] Schoen, A.H., Rosenstein, H., Stanzione, K.A., and Wisniewski, J.S., "User's Manual for VASCOMP II, Volume IV", Prepared by the Boeing Vertol Company, 1980.
[6] Carman, P., and Tigwell, P., Inside CATIA, OnWord Press, Santa Fe, New Mexico, 1998.
[7] Bauchau, O.A., "DYMORE, User's and Theory Manual", Georgia Institute of Technology, School of Aerospace Engineering, 2001.
[8] Mitchell, D.G., Ferguson, S.W., and Sponso, B.L., "Evasive Maneuver Criteria Evaluation Program (EVMCEP) User's Manual", Prepared by Systems Technology, Inc., August 1989.
[9] MATLAB Reference Guide, The Math Works Inc., October 1992.
[10] "PC Based Cost Model Developed by Bell Helicopter", Bell Helicopter, 1999.
[11] "PRISM User's Manual Version 1.0", Prepared by the Reliability Analysis Center, Rome, New York, 2000.
[12] "Interim Airworthiness Criteria, Powered-Lift Normal Category Aircraft", Department of Transportation, Federal Aviation Administration, Fort Worth, Texas, December, 1989.
[13] Storm, S., HH-60 Service Technician, Telephone Interview, USCG Aircraft Repair & Supply Center, Elizabeth City, North Carolina, February 2001.
[14] LTJG Brandt, N., E-mail interview, Air Station Clearwater, Florida, Feb 2001.
[15] Folds, D., AE 6332 Rotorcraft Design Lecture, Georgia Tech Research Institute, Georgia, February 2001.
[16] Thompson, M. E-mail Interview, Air Methods, Englewood, Colorado, June 2001.
[17] Ruvola, D., Lieutenant Colonel, U.S. Air Force, Telephone Interview, 102nd Rescue Squadron, New York, March 2001..
[18] TM 1-1520-237-10, "Operator's Manual for UH-60 Helicopter", Headquarters, Department of the Army, October 31, 1996.
[19] AMC Pamphlet 706-201, "Engineering Design Handbook, Helicopter Engineering, Part One, Preliminary Design", Department of the Army, U.S. Army Material Command, August 1974.
[20]http://www.Honeywell.com.
[21] Wilkins, R., "Use of Predictive Perspective Guidance Displays for Increased Situational Awareness", presented at the American Helicopter Society 57th Annual Forum, Washington D.C., May 2001.
[22] Anttila, D., DeLong, K., Skaggs, M., White, S., "Cockpit and Mission System Modernization", presented at the American Helicopter Society 57th Annual Forum, Washington D.C., May 2001.
[23] http://www.rockwellcollins.com.
[24] Schmidt, R.A., Heidenreich, K., Gollnick, V., "A Display and Control Concept for Helicopter Flight in Adverse Weather", presented at the American Helicopter Society 57th Annual Forum, Washington D.C., May 2001.
[25] Defense Helicopter, "Military Helicopter Handbook 2001", The Shephard Press, England, 2001.
[26] Loewy, R.G., "Recent Developments in Smart Structures with Aeronautical Applications", Presented to the 37th Israel Annual Conference on Aerospace Sciences Proceedings, 1997.
[27] Chopra, I., "Status of Application of Smart Structures Technology to Rotorcraft Systems", Presented to the Innovation in Rotorcraft Technology, Royal Aeronautical Society, London, UK, June 25-26, 1997.
[28] Loewy, R.G., "Recent Developments in Smart Structures with Aeronautical Applications", Presented to the 37th Israel Annual Conference on Aerospace Sciences Proceedings, 1997.
[29] ibid.
[30] Fink, D.A., Hawkey, T.J., Gaudreau, M.P.J., Wellman, B., and Ormiston, R.A., "An Electromagnetic Actuator for Individual Blade Control", Presented at the 56th Annual Forum of the American Helicopter Society, Virginia Beach, Virginia, May 2-4, 2000.
[31] Prechtl, E.F., and Hall, S.R., "Design of a High-Efficiency Discreet Servo-Flap Actuator for Helicopter Rotor Control", Presented at SPIE's North American Symposium on Smart Structures and Materials Proceedings, San Diego, California, March 1997.
[32] "Physik Instrumente", Product Catalog, Polytech GmbH, Waldbronn, Germany, 1998.
[33] Hanagud, S., and Roberts, P., "Piezo Stack Energy Storage Hybrid Actuator", and "Reverse Vibration Absorber to Amplify the Displacement of Piezoceramic Stack Based Actuators (Reverse Vibration Absorber)", U.S. Patents Reference 2215 (Pending) and 2216 (Pending), respectively, Georgia Institute of Technology, November 4, 1999.

[34] Armanios, E.A., and Dancila, D.S., "Apparatus and Method for Aerodynamic Blowing Control Using Smart Materials", Georgia Institute of Technology, U.S. Patent 5,791,601, August 11, 1998, and U.S. Patent 6,142,425, Atlanta, Georgia, November 7, 2000.
[35] ibid.
[36] ibid.
[37] Mavris, D.N., Schrage, D.P. and Galloway, T.L. "Mathematical Formulation and Design Methodology for a Tip-Jet Driven High Speed Rotorcraft Concept", Georgia Institute of Technology, Atlanta, Georgia, 1991.
[38] http://www.aviationtoday.com.
[39] Liu, Y., Sankar, L., Englar, R., Ahuja, K., "Numerical Simulations of the Steady and Unsteady Aerodynamic Characteristics of a Circulation Control Wing Airfoil", AIAA Paper 2001-0704, Georgia Institute of Technology, Atlanta, Georgia, 2001.
[40] ibid.
[41] "Physik Instrumente", Product Catalogue, Polytech GmbH, Waldbronn, Germany, 1998.
[42] Liu, Y., Sankar, L.N., Englar, R.J., and Ahuja, K.K., "Numerical Simulations of the Steady and Unsteady Aerodynamic Characteristics of a Circulation Control Wing Airfoil", Georgia Institute of Technology, Atlanta, Georgia, 2001.
[43] "Aeronautical Design Standard ADS-33 - Handling Qualities, Rotary Wing", United States Army Aviation Systems Command, December 1985.
[44] Calise, A.J., Rysdyk, R.T., "Non-linear Adaptive Flight Control Using Neural Networks", IEEE Control Systems, December 1998.
[45] Horn, J., Calise, A.J., Prasad, J.V.R., O'Rourke, M., "Flight Envelope Cueing on a Tiltrotor Aircraft Using Neural Network Limit Prediction", Georgia Institute of Technology, Atlanta, GA, Boeing Helicopters, Philadelphia, PA, Presented at the 54th AHS Forum.
[46] Supplement to TM 55-1520-237-MTF, "Maintenance Test Flight Manual, UH-60 Helicopter", Headquarters, Department of the Army, November 13, 1990.
[47] Narramore, J., E-mail Interview, Bell Helicopter Textron, Fort Worth, Texas, April 2001.
[48] Liu, Y., Sankar, L., Englar, R., Ahuja, K., "Numerical Simulations of the Steady and Unsteady Aerodynamic Characteristics of a Circulation Control Wing Airfoil", AIAA Paper 2001-0704, Georgia Institute of Technology, Atlanta, Georgia, 2001.
[49] Kuethe, A., Chow, C., "Foundation of Aerodynamics", John Wiley and Sons, Inc., New York, 1986.
[50] Popelka, David, Lindsay, David, Parham, Tom, Berry, Victor, Baker, Donald, "Results of an Aeroelastic Tailoring Study for a Composite Tiltrotor Wing", Bell Helicopter Textron, Inc., Presented at the 51st Annual AHS Forum, Fort Worth, Texas, 1995.
[51] Bauchau, O.A, "DYMORE; User's and Theory Manual", Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, Georgia, 1998.
[52] Alexander, H.R., Smith, K.E., McVeigh, M.A., Dixon, P.G., McManus, B.L., "Preliminary Design Study of Advanced Composite Blade and Hub and Nonmechanical Control System for the Tilt-Rotor Aircraft", Boeing Vertol Company, Philadelphia, Pennsylvania, 1979.
[53] www.cranfield.ac.uk/sims/quality/quality1/
[54] Internet Web Address: http://adg.stanford.edu/aa241/structures/structuraldesign.html.
[55] Schrage, D.P., "Fundamentals of Helicopter Fatigue Life Determination", Presented at the AHS Specialists' Meeting on Helicopter Fatigue Methodology, St. Louis, Missouri, 1980.
[56] Cronkhite, J.D., "Design of Airframe Structures for Crash Impact", Presented at the AHS National Specialist's Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.
[57] Simula Government Products, Inc., "Energy Absorbing Crew Seat for UH-60 Blackhawk (S-70 Searies)", Phoenix, Arizona, 2001.
[58] Niu, Michael C.Y., Composite Airframe Structures, Conmilit Press Ltd., Hong Kong, 1992.
[59] www.airweb.faa.gov
[60] Prouty, R., Helicopter Performance, Stability and Control, Krieger Publishing Co., Malabar, Florida, 1990.
[61] Smailys, H., "Advanced Technologies applied to PT6C-67A Tiltrotor Engine Design", Presented at the Tiltrotor/Runway Independent Aircraft Technology and Applications Specialists' Meeting of the American Helicopter Society, Arlington, Texas, March 20-21, 2001.
[62] "2001 Request for Proposal (RFP) for Advanced Rotor Control Concepts", Sponsored by The Boeing Company and The American Helicopter Society International, p. 12.
[63] Smailys, H., "Advanced Technologies applied to PT6C-67A Tiltrotor Engine Design", Presented at the Tiltrotor/Runway Independent Aircraft Technology and Applications Specialists' Meeting of the American Helicopter Society, Arlington, Texas, March 20-21, 2001.

[64] ibid.
[65] ibid.
[66] http://www.vtol.org/IHPTET.HTM.
[67] ibid.
[68] ibid.
[69] Bell Helicopter Company, "Proposal Phase I, V/STOL Tiltrotor Research Aircraft, Volume II", Fort Worth, Texas, June 1972.
[70] FAA System Safety Handbook, http://nasdac.faa.gov.
[71] http://www.teledyne-controls.com.
[72] ibid.
[73] Bell Helicopter Company, "Conceptual Design NASA Contract NAS2-6599-Volume I, Report 300-099-005", Fort Worth, Texas.
[74] "PC Based Cost Model Developed by Bell Helicopter", Bell Helicopter, 1999.
[75] ibid.
[76] Bell Helicopter, "BA-609 in a Search and Rescue Configuration", Presentation to U.S. Coast Guard.
[77] http://www.uscg.mil/datasheet/dataindx.htm.
[78] Bell Helicopter, "BA-609 in a Search and Rescue Configuration", Presentation to U.S. Coast Guard.
[79] Niu, Michael C.Y., Composite Airframe Structures, Conmilit Press Ltd., Hong Kong, 1992.
[80] Edwards, B.D., Conner, D.A., Decker, W.A., Marcolini, M.A., Klien, P.D., "NASA/ARMY/Bell XV-15 Tiltrotor Low-Noise Terminal Area Operations Flight Research Program", Presented at the Tiltrotor/Runway Independent Aircraft Technology and Applications Specialists' Meeting of the AHS, Arlington, Texas, March 20-21, 2001.
[81] www.faqs.org/faqs/active-noise-control-faq.
[82] "Certification Program Plan for the BellBoeing 609 Civil Tiltrotor FAA Project TC 1416RC-R", Bell Helicopter Textron Inc., and The Boeing Company, December 18, 1996.
[83] FAR Part 36, "Noise Standards", Office of the Federal Register, Washington, DC, October 13, 1999, Appendix G.
[84] TM 1-1520-237-10, "Operator's Manual for UH-60 Helicopter", Headquarters, Department of the Army, October 31, 1996, pp. 5-23.

APPENDIX C

Teamcenter Systems Engineering Install Notes

"Teamcenter Systems Engineering"

Pre-Installation Notes

By: Pete Hart
Email: pete@twinbeach.org
Phone: 404-245-2034 (cell)

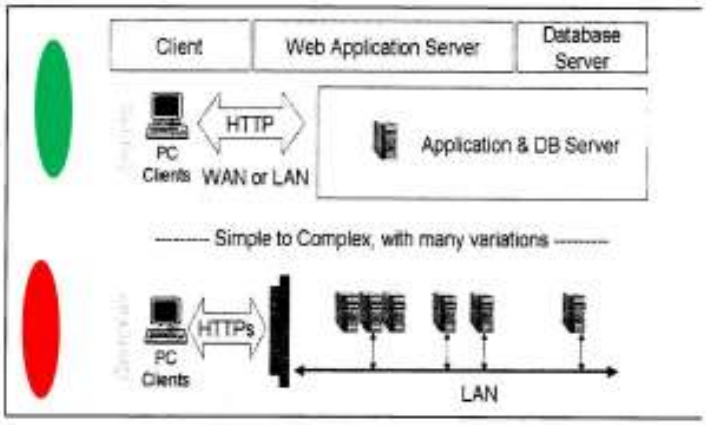
March 27, 2009

Contents

TCSE Architecture
Microsoft Virtual PC
Pre-Requisite Software Installs
PRE-TCSE Install: Versant Database Install

TCSE Environment Selection

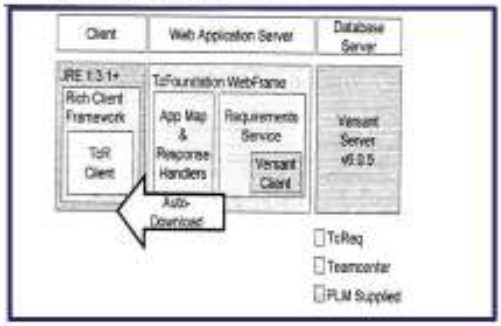
We are selecting the top option here.



TCSE Environment Selection

You can install TCSE in a number of ways:

1. **All on one machine (either all on Virtual PC, or all on PC)**
2. **Server install on a Virtual PC, Client on regular**
3. **Network distributed with multiple servers**



Instructions for configuring VPC

Install Microsoft Virtual PC 2007. It's available to download from http://www.microsoft.com/windows/virtualpc/default.mspx

You will also need to install and configure a "loopback adapter" to access the Virtual PC Environment as a separate Server.

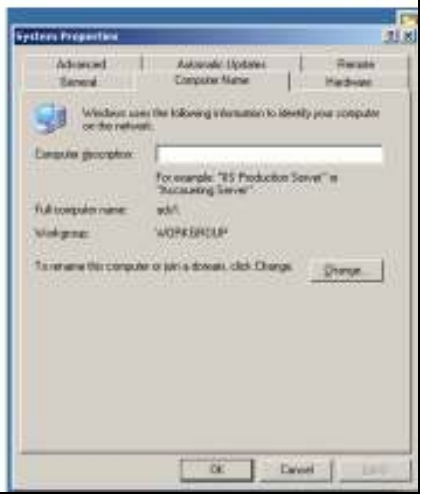
Virtual PC Re-Start

Note that Windows Server 2003 is the OS for the Virtual PC.

Virtual PC Re-Start

Do not use the ctrl-alt-delete from the computer!!! You need to use the ctrl-alt-delete contained under the "Action" pulldown menu, in the Virtual PC.

Virtual PC Name: Localhost=ads1



Server OS and setup

Turn **OFF** Automatic Updates!!!

Installing the Loopback Adapter

Networking for the VPC:

Loopback Adaptor (Not required If you are running TCX client and server on VPC)
If you have not installed the loopback adaptor on your local Windows machine, please follow the How to install the Microsoft Loopback adapter in Windows XP instructions located at:
http://support.microsoft.com/default.aspx?scid=kb;en-us;839013

Installing the Loopback Adapter

How to install the Microsoft Loopback adapter in Windows XP

SUMMARY

The Microsoft Loopback adapter is a testing tool for a virtual network environment where network access is not available. Also, you must use the Loopback adapter if there are conflicts with a network adapter or with a network adapter driver. You can bind network clients, protocols, and other network configuration items to the Loopback adapter, and you can install the network adapter driver or network adapter later while retaining the network configuration information. You can also install the Loopback adapter during the unattended installation process.

Installing the Loopback Adapter

Manual installation
To manually install the Microsoft Loopback adapter in Windows XP, follow these steps:

1. Click Start, and then click Control Panel.
2. If you are in Classic view, click Switch to Category View under Control Panel in the left pane.
3. Double-click Printers and Other Hardware, and then click Next.
4. Under See Also in the left pane, click Add Hardware, and then click Next.
5. Click Yes, I have already connected the hardware, and then click Next.
6. At the bottom of the list, click Add a new hardware device, and then click Next.
7. Click Install the hardware that I manually select from a list, and then click Next.
8. Click Network adapters, and then click Next.
9. In the Manufacturer box, click Microsoft.
10. In the Network Adapter box, click Microsoft Loopback Adapter, and then click Next.
11. Click Finish.

After the adapter is installed successfully, you can manually configure its options, as with any other adapter. If the TCP/IP properties are configured to use DHCP, the adapter will eventually use an autonet address (169.254.x.x/16) because the adapter is not actually connected to any physical media.

Note By default, TCP/IP properties are configured to use DHCP.

Installing the Loopback Adapter

Set the loopback adaptor on your local Windows XP machine as follows:

In Windows XP navigate to your Desktop
Right-click on My Network Places and select Properties
Right-click on the newly added Network Connection using Loopback Adaptor and select Properties
Select Internet Protocol (TCP/IP) and click on the Properties button
Select Use the following IP address and set the following values
- IP address: 192.168.1.1 (If this address conflicts with another on your network you can use any address here as long as the last number is one less than the one on the VPC machine)
- Subnet mask: 255.255.255.0

Installing the Loopback Adapter

Configure the VPC (Virtual Machine) Network Connection as follows:
In VPC Windows Explorer navigate to your Desktop
Select Start>Control Panel>Network Connections>Local Area Connection
Select Properties
Select Internet Protocol (TCP/IP) and click on the Properties button
Select Use the following IP address and set the following values
IP address: 192.168.1.2
Subnet mask: 255.255.255.0

Installing the Loopback Adapter

Error on ping.... IN REAL LAPTOP...

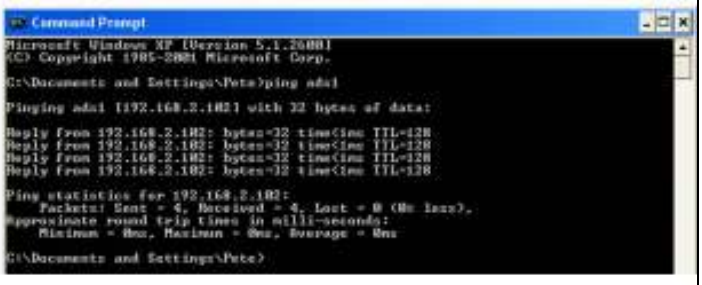
1.|Removed the ads1 ip address from the .../etc/hosts file on the laptop machine. ..

2.|Set Virtual PC Local Area Connection to:

Obtain an IP address automatically.

This seemed to work... the ping on the laptop shows that the Virtual PC is up, running, and in communication through the loopback adapter.

Installing the Loopback Adapter



Assigned ip address for "ads1" appears to be:
192.168.2.102

192.168.2.101

VPC Setup and Backup

Once you have the Microsoft Virtual PC configured, and the right Operating System Installed (Microsoft Windows Server 2003.sp1)

Take a step back and make a backup copy of this environment so that you can work with it later, if you need to.

Copy it to an adequately sized hard drive, and change the name to something descriptive, like

TCSE.V8.3.09.vpc

Or

WIN2003SP1.VPC

Pre-Install gathering files

Ok. This is the start of the TCSE Install Notes.

First of all, there must be the necessary pre-requisite software. I prefer to download all of these as the zipped installer files into a single folder marked as TCSE.PREREQS. They are:

Microsoft Office 2007, Visio,...

Adobe Acrobat Reader 8

Internet Explorer 6

Apache Tomcat 5.5.25, 6.0.x

JRE 1..6.0_07

JDK 1.5.0_14, 1.6.0_07

Then find the DVD or Zip file for the TCSE application, and bring it into a second folder with an obvious naming, like: TCSE.V8.INSTALL.ZIPPED

These should all be located in your Program Files folder on the laptop, which is called SEDNA.

Pre-Install gathering files

There are several required pieces of software that are REQUIRED to be installed BEFORE you install TCSE within the VPC. Note that there are specific versions of these software tools, that may be significantly older than the current version. In most cases, you MUST use the older dated version for TCSE. If it is possible to update the versions of these tools later on, that should be accomplished AFTER the initial install, testout, and backup of the database and environment.

-MS Winsdows: Server 2003 SP1 (or XP SP2 for client only on the Laptop)
-Microsoft .NET Framework: .Net 1.1 AND .Net 2.0
-Java IE Plugin
- JRE 1.5.0 or 1.4.2
- Java SDK 1.5.0.13
-Apache Tomcat Version 5.5.25
-MS Office 2007 (Word, Excel, Powerpoint, Visio, Project)
-SDI DFSS Software (Triptych)
- Matlab 2007a (Student Edition)
- TCSE v8.0 CD-Set or Download from the Siemens GTAC website.

-It is best to gather all of these software tools as zipped executable files first, then install each of them in order.

Transfer files to VPC

You need to transfer all of the files from your hard drive on the laptop, to the "virtual" hard drive on the VPC Image. This is done through mapping the laptop as a Z drive, or drag and drop. I have done both.

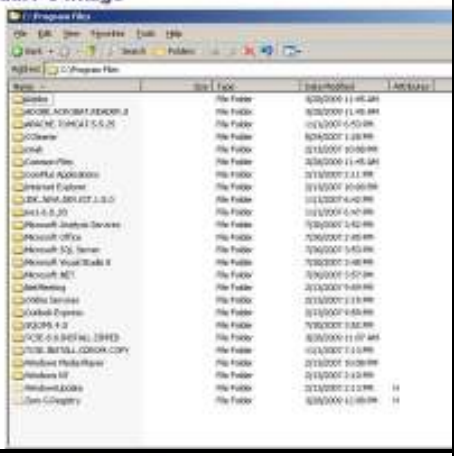
Once you have them all in there,

Start installing the components in the following order:

0000. Windows Server 2003 sp1
000. Internet Explorer
00. Microsoft Office 2007
0. Microsoft.NET
1. Java IE Plugin
2. Java RTE
3. Java SDK
4. SDIOFSS Tools
5. Apache Tomcat
6. Versant Database
7. TCSE.v8 cd set

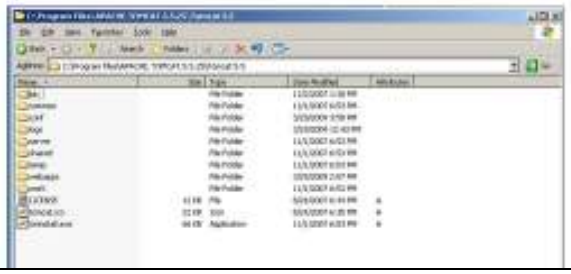
Installing the Pre-Reqs.

Program Files on the Virtual PC Image



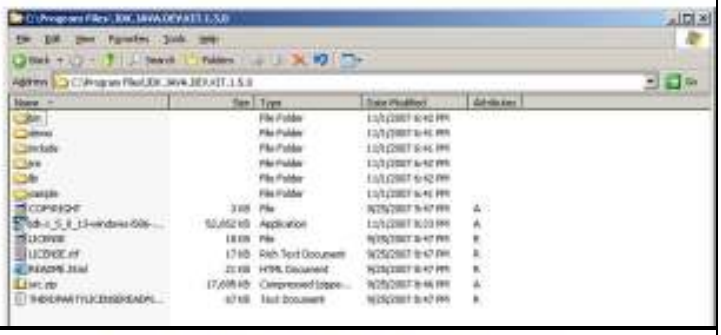
Installing the Pre-Reqs.

Apache Tomcat



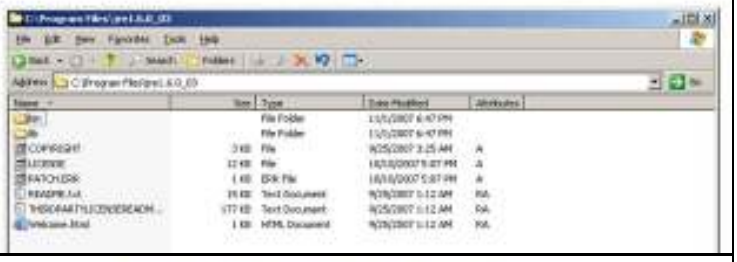
Installing the Pre-Reqs.

Java Developer Toolkit



Installing the Pre-Reqs.

Java Runtime Environment



Installing the Pre-Reqs.

Microsoft.NET

Installing TCSE?

Unzip the application for the TCSE Install and all the contents.

Apparently they have changed the install for TCSE.V8, and you now have to install the Versant Database manually, BEFORE you install TCSE.V8.

I attempted to install the TCSE first, and this is the screens that I got shown on the following page.

Install Versant BEFORE TCSE!!

Ja;fdkj;kj

'laeljobv io

Versant Installer Process

Versant Installer Process

Ja;fdkj;kj

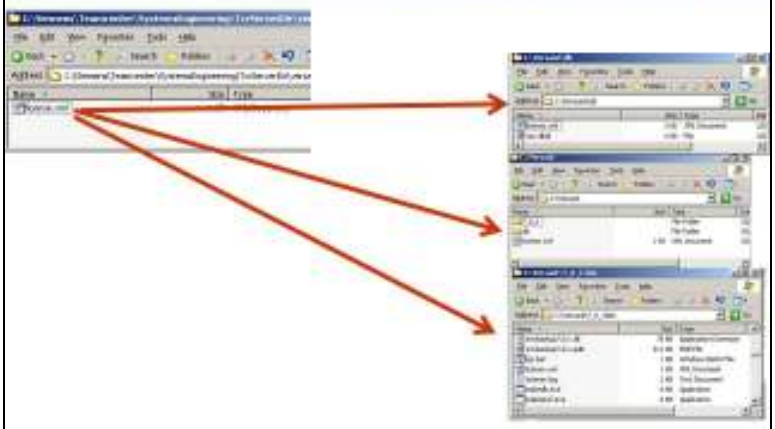
'laeljobv ioan rqhn adhha

Versant Installer Process-Completion

Ja;fdkj;kj

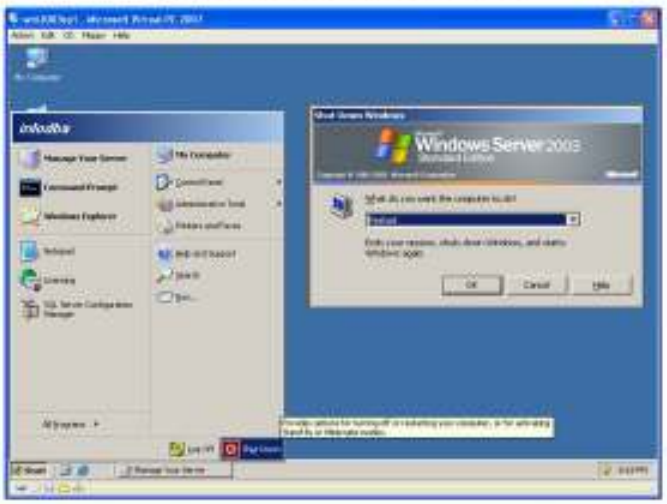
'laeljobv ioan rqhn adhha

Versant Installer Process-Completion



Install the Versant license… I didn't know where it went, so I put it all over.

Virtual PC Re-Start

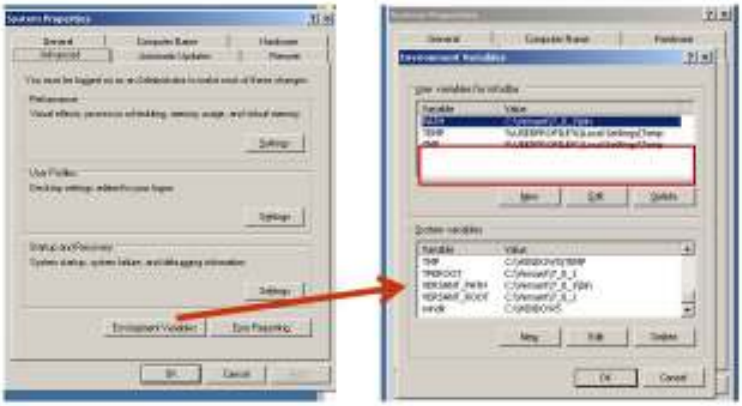


Checking the Versant install

Application Server:
The following commands can be used to ensure that the application server can communicate with the database server across the network:
oscp –l @<dbserverhostname>
Sample output:
(This shows the Versant information of the database server machine.)
oscp -l @rsi6s001
Versant Product Version: 7.0.1.3
Versant Root Path: d:\TCSE\TCRSERVERDIR\versant
Versant Runtime Path: d:\TCSE\TCRSERVERDIR\versant
Versant DB Directory: d:\TCSE\TCRSERVERDIR\versant\db
Versant osc-dbid node name: RSI6S001
Versant osc-dbid path: d:\TCSE\TCRSERVERDIR\versant\db
itest -v rsi6s001
Sample output:
host name: rsi6s001 IP addr: xxx.xxx.xxx.xxx
Connection to rsi6s001 successful.

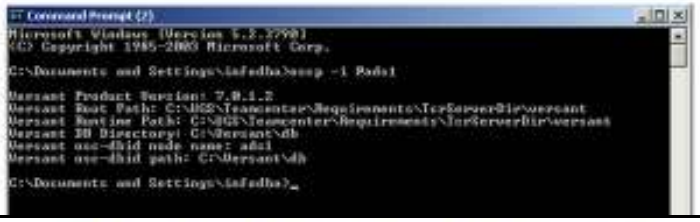
Checking the Versant install

This is a mix of wrong things. The Root Path and the Runtime path should be similar to the db directory path!!! And they are not. The UGS directory is an old one...



Checking the Versant install

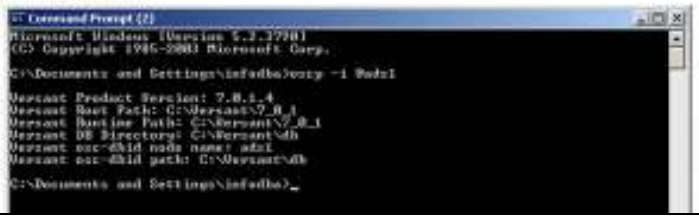
This is a mix of wrong things. The Root Path and the Runtime path should be similar to the db directory path!!! And they are not. The UGS directory is an old one...



Checking the Versant install

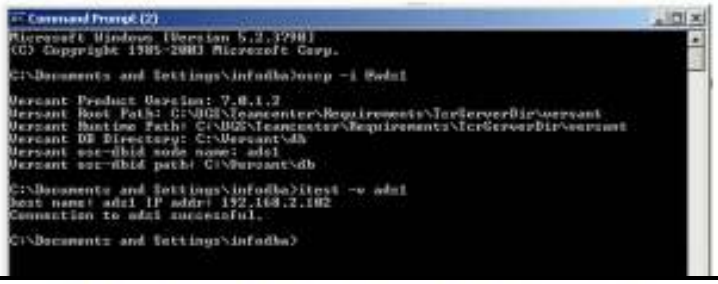
This is what it should really look like. This is correct.

The problem was in the definition of USER VARIABLES. Do not create USER Variables. Only set the System Variables to the correct values. Actually, the Versant installer did them correctly, automatically, including a re-write of them.



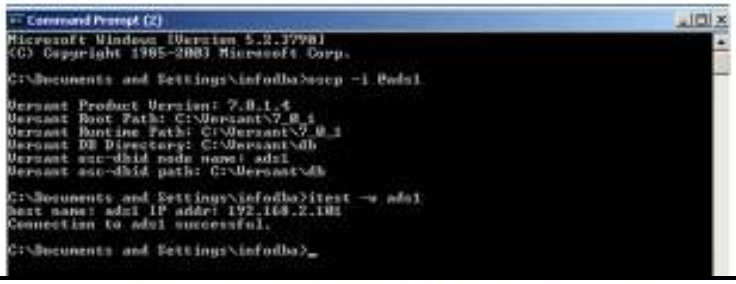
Checking the Versant install

The itest is ok, but the stuff above it is wrong!!!

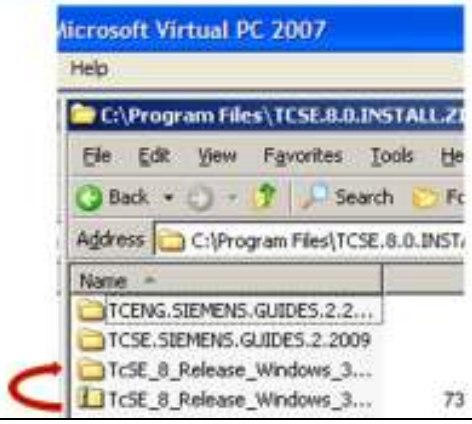


Checking the Versant install

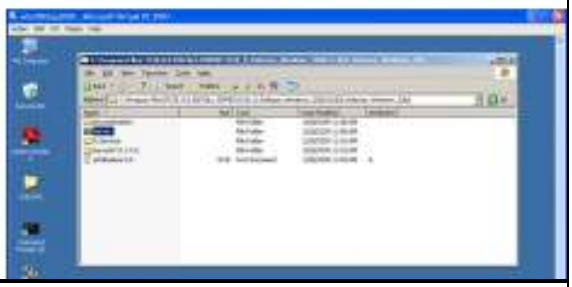
This is the right stuff here!!!



Unzip the Install Folder



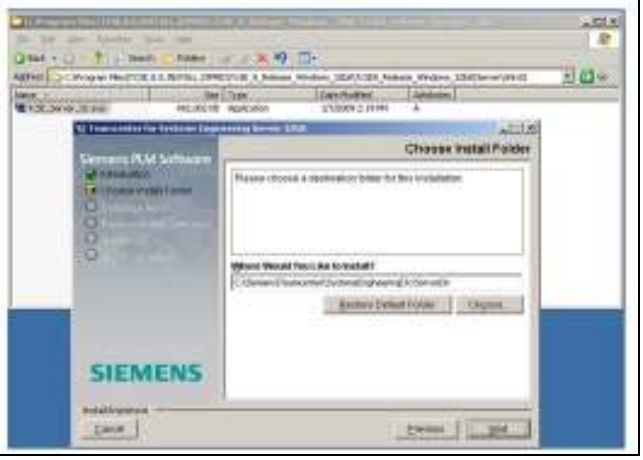
Install Source=Server Directory



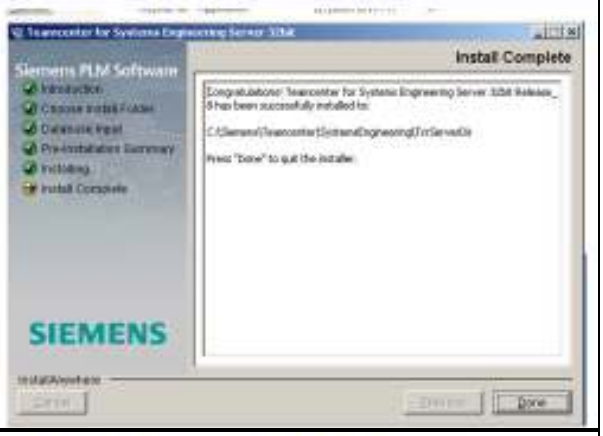
It may take several minutes before the installation window appears. If you choose not to execute the installation from the DVD-ROM, copy the appropriate executable program to a directory on your system and execute it. If you have downloaded the installable from the Siemens FTP site,extract the zip file and continue.

TCSE Installation

TCSE Installation



TCSE Installation

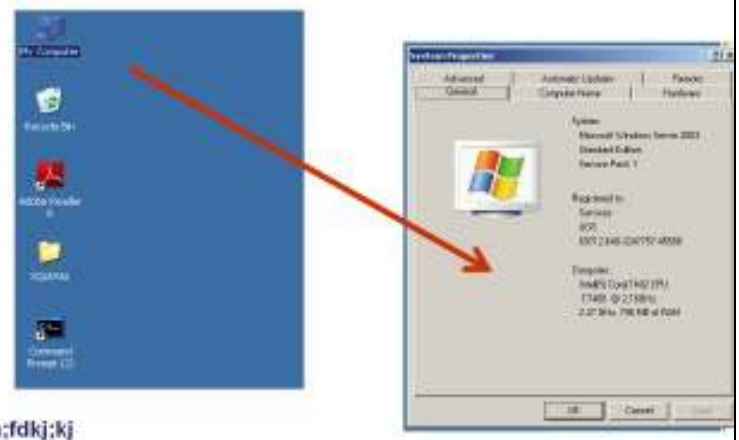


Deploy Versant License

Set Environment Variables

Required Variables for Windows
The following environment variables must be set for the user who creates and
manages the Versant database (TCR_db) on Windows machines:
• Set VERSANT_ROOT to point to the root level of your Versant installation.
• Set PATH to the Versant bin directory /versant/bin.
These variables must be set on both the application server and the database server.

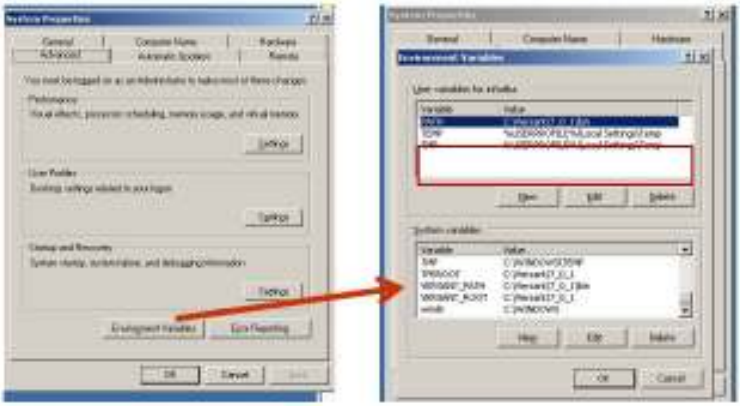
Set Environment Variables



Ja;fdkj;kj

'laeljobv ioan rqhn adhha

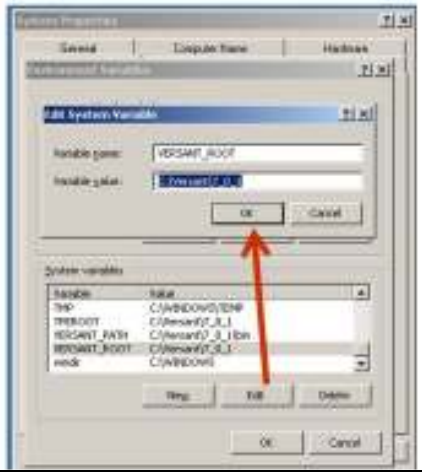
Set Environment Variables



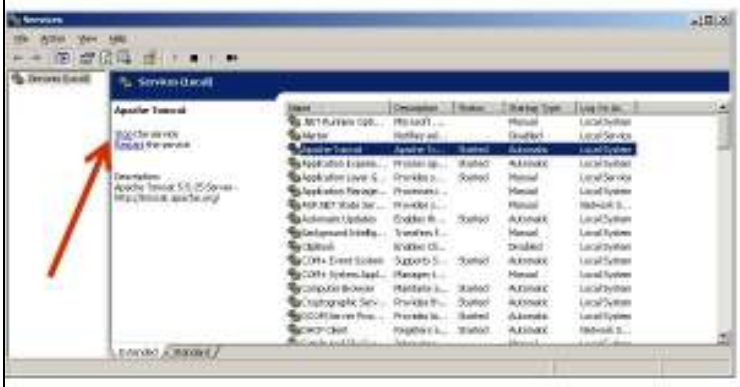
The Versant Path and Root Variables should be created automatically, but they need to be checked. Do not create User Variables.

Set Environment Variables

You should not have to edit these, but, just in case you need to …



War File deployment



Make sure that Tomcat is running to deploy the war file…

Check to see if Tomcat is running:

It is best to test this inside of the Virtual PC first, as there may be internet connection issues between the Virtual pc, and the laptop that may need to be resolved.

This is a website address in Internet Explorer. The address to check on the Tomcat install is: http://(localhost):8080/index.jsp

If you can see this webpage, then Tomcat is up and running!

This is the screen for starting Tomcat

The big Fix up!!

There needs to be a re-cap here.

What was the error? TCSE 2005 was previously installed. The new TCSE.v8 uses a new installer (for good reason!!). So the Versant database was re-installed in a new location up on the Root directory C:\

And the TCSE.V8 was installed as automatically done in the TCSE.V8 installer.

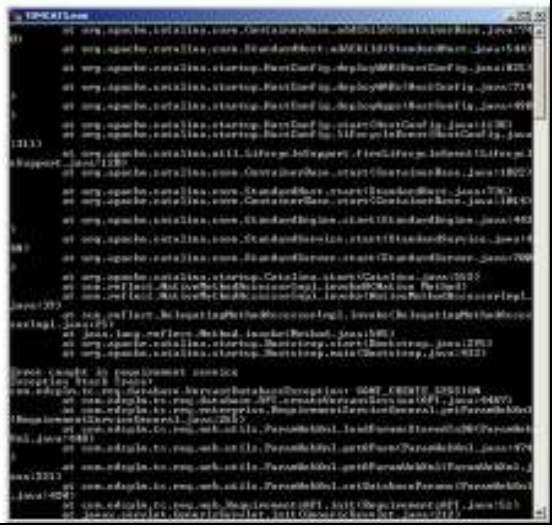
But, there was a problem, because the .V8 installer did not remove the older version of TCSE 2005!!!! So I had to go in and manually remove the tcr.war file from the Tomcat Webapps sub-folder, and remove the tcr folder(s) as well. (there was one for the tcr.dfss.war too) In addition, I had to go in and manually remove a "UGS" install directory from the "Program Files" folder, as well. Then, a re-boot was necessary.

Once the re-boot of the Virtual PC was completed, I went into the "SERVICES" area, and stopped BOTH the VERSANTD application, and the Apache Tomcat Webserver.

I deployed the new TCSE.V8 tcr.war file to the Tomcat Webapps folder.

Then I got OUT of the "Services" area, and started the Tomcat5.exe on the desktop. That gave the listing in the black window on the previous pages. It went on and on, because it had to configure the new tcr.war file from the new TCSE.V8 . After it was done, I started both "Services": Apache Tomcat and the VERSANTD

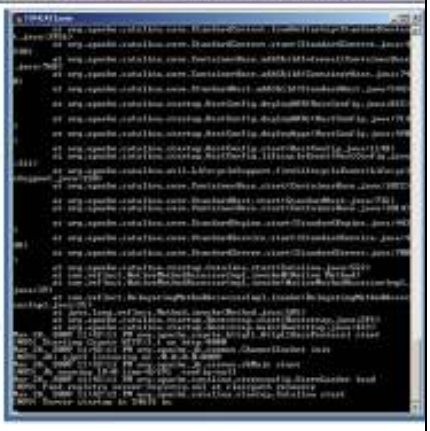
This is the screen for starting Tomcat-Correct!



This is the screen for starting Tomcat-Correct!

Notice the last entry here! What is all of this? It is the Web server (Tomcat) loading in and configuring the TCSE environment, after successful load-in of the tc.

But even here, the Database is not linked to the TCSE Application. This needs to be fixed…



Starting up the TCSE8 client…

It is best to test this inside of the Virtual PC first, as there may be internet connection issues between the Virtual pc, and the laptop that may need to be resolved.

This is a website address in Internet Explorer. The address to check on the TCSE.V8 install is: http://(localhost):8080/tcr

If you can see this webpage, then TCSE.V8 is up and running!

Starting up the TCSE8 client…

These web pages should SNAP right up!! None of this lame time lapse loading. They are lightweight, and running locally! If they take more than a few seconds to load, then there is a problem…

Notice that the client looks exactly the same on the Virtual PC as on the Laptop, except that the browsers are different.

Client on the laptop

Once the communication issues are resolved, then you can try to open the client from the laptop, outside of the Virtual PC. This will let you know if your loopback is working correctly, with the ip addresses assigned correctly.

"Teamcenter Systems Engineering"

Installation and Configuration Notes

By: Pete Hart

Email: pete@twinbeach.org

Phone: 404-245-2034 (cell)

March 27, 2009

REFERENCES

[1] "The Egg Chart" Chart-Image, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[2] DoD Directive 5000.1. http://www.dtic.mil/whs/directives/corres/pdf/500001p.pdf Accessed 3/1/2009

[3] "DoD Regulation 5000.2-R" DoD 5000.2-R Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs" Office of Under Secretary of Defense (Acquisition, Technology, and Logistics) June 10, 2001. http://www.acq.osd.mil/ie/bei/pm/ref-library/dodi/p50002r.pdf Accessed 3/1/2009

[4] "DoD 5015.02-Standard: Electronic Records Management Software Applications Design Criteria Standard" Assistant Secretary of Defense for Networks and Information Integration/Department of Defense Chief Information Officer. April, 25, 2007. http://www.dtic.mil/whs/directives/corres/pdf/501502std.pdf Accessed 3/1/2009

[5] Memo to DoD Components, Office of Under Secretary of Defense (Acquisition, Technology, and Logistics). DoD 5000.2-R Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs, June 10, 2001.

[6] "Right Data, Right People, Right Time" Quote, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[7] "A PLM Enabled Design Engineering Methodology" Chart-Image, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[8] "A Methodology for Technology Identification, Evaluation, and Selection in Conceptual and Preliminary Aircraft Design" Phd Thesis, Michelle Renee Kirby, Georgia Institute of Technology, Atlanta, Georgia November 8, 2006

[9] "A PLM Enabled Digital Systems Engineering Environment" Chart-Image, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[10] "18th Annual Graduate Student Design Competition-Request for Proposals" American Helicopter Society (AHS) 2000.

[11] "The Perfect Storm" Sebastian Junger @1997, Harper Collins Publishing, New York, New York

[12] "Close Air Support/ Escort Rotorcraft" Final Proposal to the AHS Graduate Student Design Competition, Georgia Tech Rotorcraft Engineering Student Design Team, Dr. Daniel P. Schrage, Georgia Institute of Technology, 1997

[13] "Uccello- Civil Aviation Variable Diameter Tiltrotor" Final Proposal to the AHS Graduate Student Design Competition, Georgia Tech Rotorcraft Engineering Student Design Team, Dr. Daniel P. Schrage, Georgia Institute of Technology, 1999

[14] "Kingfisher-Advanced Search and Rescue Tiltrotor" Final Proposal to the AHS Graduate Student Design Competition, Georgia Tech Rotorcraft Engineering Student Design Team, Dr. Daniel P. Schrage, Georgia Institute of Technology, 2001

[15] Final Proposal to the AHS Graduate Student Design Competition, Georgia Tech Rotorcraft Engineering Student Design Team, Dr. Daniel P. Schrage, Georgia Institute of Technology, 1997. Image Copyright 2009, Peter B. Hart, Twin Beach Space Systems, Atlanta, Georgia

[16] "What is System Engineering" INCOSE website @ 1996-2009 INCOSE http://www.incose.org/practice/whatissystemseng.aspx Accessed 3/1/2009

[17] "Engineering Design, 3rd Edition (A Materials and Processing Approach)", Dieter, George, @2000, McGraw-Hill Higher Education, New York, New York

[18] "BAMS-Broad Agency Announcement: Statement of Objectives (SOO)for the United States Navy Broad Area Maritime Surveillance (BAMS) Unmanned Aircraft System (UAS)-System Development & Demonstration (SDD) Phase-DRAFT, Version 4.0" Naval Air Systems Command, Patuxent River, MD, November, 2006 http://www.fbodaily.com/archive/2006/11-November/16-Nov-2006/FBO-01180879.htm Accessed 2/20/2007

[19] "The House of Quality," Hauser, J. R. and Clausing, D., Harvard Business Review, vol. 66, no. 3, pp. 63_, 1988.

[20] [1] "A Hierarchical Requirements Modeling Methodology Applied to the Design off Unmanned Aerial Vehicles" Dufresne, Stephane, Phd. Thesis, Georgia Institute of Technology, 2008.

[21] "A Generic Product Lifecycle" Chart-Image, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[22] Quote, Steve Wegner (retired), Product Data Initiative (PDI) Program, Lockheed Martin Aeronautics Company (LMAC), @2003

[23] "MBOM" Wikipedia Webpage, Wikipedia Foundation, Inc. 2008. http://en.wikipedia.org/wiki/Manufacturing_bill_of_material Accessed 3/1/2009

[24] "Engineering Documentation Control Practices and Procedures" Ray E. Monahan, @1995, Marcel Dekker, Inc., New York, New York

[25] "Slate-A UGS Teamcenter Product" Siemens PLM Software. http://www.paper-review.com/tools/sas/vencon.php?vendor=SLATE%206.5%20(a%20UGS%20Teamcenter%20product) Accessed 3/1/2009

[26] "Siemens Product Lifecycle Management Software, Inc.", A division of Siemens Automation and Drives, Plano, Texas. http://www.plm.automation.siemens.com/en_us/

[27] "Teamcenter Systems Engineering" Siemens Product Lifecycle Management Software, Inc., Plano, Texas. 2008 http://www.plm.automation.siemens.com/en_us/products/teamcenter/solutions_by_product/systems_engineering.shtml Accessed 3/1/2009

[28] "Teamcenter Systems Engineering 2007- Server Installation Manual" REQ00005-H. Siemens Product Lifecycle Management Software, Inc., Plano, Texas. 2008
-Installation Guide
-Database Administration Guide
-Project Administration Guide
-DFSS Integration Guide
-User Guide

[29] "Microsoft Windows" Microsoft Corporation, Inc., Bellevue, WA http://www.microsoft.com Accessed 3/1/2009

[30] "Java" Sun Microsystems, Inc. Santa Clara, CA, http://www.java.sun.com Accessed 3/1/2009

[31] "Versant Database Software" The Versant Corporation, Inc. Redwood City, CA http://www.versant.com Accessed 3/1/2009

[32] "Apache Tomcat Web Application Server" The Apache Software Foundation, Inc. http://tomcat.apache.org/ Accessed 3/1/2009

[33] "Engineering Documentation Control Handbook, 2nd Edition (Configuration Management in Industry" Frank B. Watts, @2000, Noyes Publications/William Andrew Publishing LLC, Norwich, New York

[34] "Department of Defense Architectural Framework", Wikipedia Web page http://en.wikipedia.org/wiki/Department_of_Defense_Architecture_Framework Accessed 3/1/2009

[35] "A Digital Manufacturing Enterprise Data Infrastructure Configuration, featuring a Legacy Data Modeling and Simulation Repository (Library)". Chart-Image, Peter B. Hart, Twin Beach Space Systems, @2009. Atlanta, Georgia

[36] "Teamcenter Engineering" Siemens Product Lifecycle Management Software, Inc., Plano, Texas. 2008

[37] "Oracle Database Software" Oracle Corporation, Inc. http://www.oracle.com/index.html Accessed 3/27/2009

[38] "DB2 Database Software" IBM Corporation, Inc. http://www-01.ibm.com/software/data/db2/ Accessed 3/27/2009

[39] "The Memory Jogger II- A Pocket Guide of Tools for Continuous Improvement and Effective Planning, First Edition" Michael Brasssard & Diane Ritter, Goal/QPC, Salem, NH, 1994

[40] "BAMS Requirements Interpretation using Teamcenter System Engineering", Presentation at PLM World 2007, Hart, Peter B., Alston, Katherine,Rohl, Peter, Advatech Pacific, Inc. Redlands, CA. 2007 https://plmworld.org/home/presentations/abstracts/2007_presentations/teamcenter/TCSE6-Hart.pdf Accessed 3/27/2009

[41] Hart, Peter B., Twin Beach Space Systems, Atlanta, Georgia @2009

[42] "Teamcenter Community" Siemens Product Lifecycle Management Software, Inc., Plano, Texas. 2008 http://www.plm.automation.siemens.com/en_us/products/teamcenter/solutions_by_product/community_collaboration.shtml Accessed 3/1/2009

[43] "Original 2000 IPPD effort on the AHS RFP." Kingfisher IPR #1Final, Georgia Tech Aerospace Engineering, Graduate AHS Design Competition Team, November, 2000

[44] "Flowchart of Quantitative Requirements Analysis Tools featuring the QFD, Morphological Matrix of Alternatives, PUGH Matrix, and MADM tools." Schrage, Daniel P., Aerospace Systems Design Laboratory (ASDL), Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, 2008

[45] "Triptych-QFD Methodology Tool", Statistical Design Institute, LLC, Mckinney, Texas, 2009. http://www.stat-design.com/contact-sdi.php. Accessed 3/15/2009

[46] MIL-HDBK-881A "DoD Handbook-Work Breakdown Structure", July 30, 2005 http://www.acq.osd.mil/pm/currentpolicy/wbs/MIL_HDBK-881A/MILHDBK881A/WebHelp3/MILHDBK881A.htm Accessed 3/18/2009

[47] "LEAN Thinking-Banish Waste and Create Wealth in your Corporation", Womack, James P., Jones, Daniel T., Simon and Shuster, @1996

VITA

PETER BARTHOLOMEW HART

Summary of Experience:

Captain Peter B. Hart is the President of Twin Beach Space Systems, an Aerospace Design Engineering, and PLM Consulting firm, located in Atlanta, Georgia. Hart is the founder and former Manager of the Integrated Product Lifecycle Engineering Center at the Georgia Institute of Technology (GT-IPLE). Hart was involved in the creation of the State of Georgia Aerospace Innovation Center, and the PLM planning for the National Institute of Aerospace at NASA Langley (NIA). While working at Georgia Tech, he provided PLM instructional support at the Undergraduate, Masters, and Doctorate levels for the Georgia Tech College of Engineering. His research interests are: Aerospace Engineering, Vehicle Design Synthesis, CAD/CAE/CAM/PDM, Systems Engineering, Knowledge Capture and Management, and Modeling & Simulation in Manufacturing and Defense Systems Acquisition. He has been involved as an advisor for both Design and PLM to over 120 Advanced Aerospace Vehicle Design project teams.

Prior to attending Georgia Tech, Captain Pete was employed as a commercial fisherman on the eastern coast of the United States. During that time, he founded Twin Beach Painters, Inc., and Twin Beach Dive & Salvage, Inc. to perform diving services for the local commercial fishing industry in his hometown of Cape May, New Jersey.

For pleasure, Peter enjoys diving, fishing (with a net…), sailing, maritime history, architectural design, home renovation, gardening and foreign travel.

Education

Lower Cape May Regional High School, Cape may, New jersey
BS, Georgia Institute of Technology, Atlanta, Georgia, Aerospace Engineering
MS, Georgia Institute of Technology, Atlanta, Georgia, Aerospace Engineering

Peter B. Hart, Aerospace Design Engineer, PLM Consultant
Twin Beach Space Systems
Atlanta, Georgia
pete@twinbeach.org
404-245-2034